AD-A047 659 NAVAL AIR PROPULSION TEST CENTER TRENTON N J PROPULS--ETC F/G 21/4
EVALUATION OF THE EXTENDED USE OF FERROCENE FOR TEST CELL SMOKE--ETC(U)
OCT 77 A F KLARMAN

UNCLASSIFIED NAPTC-PE-110 NL

1 OF 2
AD
A047659

NAPTC-PE-110

ADA047659

NAVAL AIR PROPULSION TEST CENTER

TRENTON, NEW JERSEY 08628

NAPTC-PE-110	OCTOBER 1977

EVALUATION OF THE EXTENDED USE OF FERROCENE FOR TEST CELL SMOKE ABATEMENT; ENGINE AND ENVIRONMENTAL TEST RESULTS

By: A. F. Klarman

DATA IN THIS DOCUMENT ARE PRESENTED IN SI UNITS AND U.S. CUSTOMARY UNITS

DDC
DEC 14 1977
E

AD No.
DDC FILE COPY

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER NAPTC-PE-110 (14)	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER (9)
4. TITLE (and Subtitle) (6) Evaluation of the Extended Use of Ferrocene for Test Cell Smoke Abatement; Engine and Environmental Test Results.		5. TYPE OF REPORT & PERIOD COVERED Interim rept.,
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Anthony F./Klarman		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Air Propulsion Test Center Fuels and Fluid Systems Division, PE71 Trenton, New Jersey 08628		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NAVAIR AIRTASK NO. 5365360-0522-66231000
11. CONTROLLING OFFICE NAME AND ADDRESS Commander Naval Air Systems Command (AIR-5360A) Washington, DC 20361	(11)	12. REPORT DATE October 1977
		13. NUMBER OF PAGES 123
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 122p.		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release: Distribution Unlimited

D D C
DEC 14 1977
E

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Gas Turbine Engines
Jet Engine Test Cells
Smoke Abatement
Air Pollution
Fuel Additive

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Results of a test program to evaluate the feasibility of utilizing the smoke suppressant fuel additive, ferrocene, during post overhaul performance checks of gas turbine engines at Naval Air Rework Facilities (NARF's) and other lower level maintenance test facilities to reduce test cell exhaust smoke plumes to environmentally acceptable levels are presented. This test program was conducted on the following gas turbine engines: J52-P-6B, J57-P-10, J79-GE-8D, TF30-P-6C and TF41-A-2A.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

407728

4

NAVAL AIR PROPULSION TEST CENTER

TRENTON, NEW JERSEY 08628

PROPULSION TECHNOLOGY AND PROJECT ENGINEERING DEPARTMENT

NAPTC-PE-110 OCTOBER 1977

EVALUATION OF THE EXTENDED USE OF FERROCENE FOR TEST CELL SMOKE ABATEMENT; ENGINE AND ENVIRONMENTAL TEST RESULTS

Prepared by: A. F. Klarman
A. F. KLARMAN

Approved by: L. Maggitti
L. MAGGITTI

APPROVED FOR PUBLIC RELEASE:
DISTRIBUTION UNLIMITED

AUTHORIZATION: NAVAIR AIRTASK No. A5365360-0522-66231000
NAVAIR Work Unit Assignment No. NAPTC-OP7-426

TABLE OF CONTENTS

ACCESSION for
NTIS White Section
DDC Buff Section
UNANNOUNCED
JUSTIFICATION
BY
DISTRIBUTION/AVAILABILITY CODES
Dist. SPECIAL
A

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	Full Word
AESO	Aircraft Environmental Support Office
AFAPL	Air Force Aero Propulsion Laboratory
AFCEC	Air Force Civil Engineering Center
AFLC	Air Force Logistics Command
AFML	Air Force Materials Laboratory
AFSAM	Air Force School of Aerospace Medicine
ASAS	Automated Smoke Abatement System
BAAPCD	Bay Area Air Pollution Control District
NAPTC	Naval Air Propulsion Test Center
NARF	Naval Air Rework Facility
NAVAIR	Naval Air Systems Command
SMET	Simulated Mission Endurance Test

CONVERSION FACTORS: SI TO U.S. CUSTOMARY UNITS

Convert From	To	Multiply by
kilogram (kg)	pound (lb)	2.204 622
metre^3 (m^3)	gallon (gal)	$2.641\ 720 \times 10^2$

INTRODUCTION

Between 1972 and 1976, the Naval Air Propulsion Test Center (NAPTC) conducted a test program to investigate the feasibility of using a smoke suppressant fuel additive for reducing test cell exhaust smoke to acceptable levels. A visual opacity of 20 percent (Ringlemann Number (No.) 1) is the typical maximum allowable standard applied to smoke plumes throughout the United States. A total of eighteen candidate additives were evaluated in the program and ferrocene was found to be the most effective additive with the least potential health, safety and environmental problems. Reference 1 reported the results of tests conducted by NAPTC in evaluating the candidate smoke abatement fuel additives, in determining the effects of ferrocene on engines in the Navy inventory, and in assessing the health, safety and environmental effects of ferrocene. Based on these test results, the Naval Air Systems Command (NAVAIR) in references 2 and 3 authorized the use of ferrocene, with time and concentration constraints, to reduce test cell smoke emissions during jet engine performance check runs at the Naval Air Rework Facility (NARF) Alameda. Subsequent to NAVAIR approval, NARF Alameda has utilized ferrocene in J52-P-6B and J57-P-10 engines for test cell smoke abatement. During this period, no engine problems in the Fleet were identified as caused by the use of ferrocene by the NARF.

Two problems associated with the utilization of the ferrocene smoke abatement additive by the NARF have been identified. The current method of injecting the additive does not provide any means of controlling the additive flow rate or measuring plume opacity, and the allowable engine operating time with ferrocene does not completely cover the total time presently required for performance check runs, primarily due to retest requirements. An Automated Smoke Abatement System (ASAS) has recently been developed by NAPTC as a solution to the first problem. This system is capable of measuring plume opacity, determining if the plume opacity is greater than a standard (such as: 20 percent visual opacity) and injecting the minimum quantity of ferrocene necessary to reduce the plume opacity to the standard. Reference 4 describes this system and evaluation tests conducted at NAPTC, NARF Alameda and NARF North Island. During reference 5, a program for solving the second program by extending the use of ferrocene to cover all test cell engine operations (time) performed by NARF's and other lower level maintenance facilities was developed. This new program would employ an ASAS to monitor the test cell plume opacity and control the additive flow rate. By reference 6, NAVAIR assigned NAPTC the responsibility of managing and coordinating the program.

This report includes the work performed by the Aircraft Environmental Support Office, (AESO), NARF North Island; Air Force Civil Engineering Center (AFCEC), Tyndall Air Force Base; Air Force School of Aerospace Medicine (AFSAM), Brooks Air Force Base; Air Force Aero Propulsion Laboratory (AFAPL) and Air Force Materials Laboratory (AFML), Wright-Patterson Air Force Base (WPAFB); and NARF's Alameda and North Island in evaluating the feasibility of extending the ferrocene time limitation on gas turbine engines and in determining the effect of ferrocene on particulates and hydrocarbon exhaust emissions.

CONCLUSIONS

1. Individual ten-hour performance tests conducted on J52-P-6B, J57-P-10, J79-GE-8D, TF30-P-6C and TF41-A-2A engines employing the ASAS and ferrocene resulted in no observable adverse effects on the hot section components of these engines.

2. The operating performance of the J52-P-6B, the J57-P-10, and the J79-GE-8D engines was not measurably affected by the use of ferrocene at the concentrations necessary to maintain the test cell exhaust plume opacity at or below 20 percent visual opacity (Ringlemann No. 1).

3. The TF30-P-6C engine met model acceptance performance criteria following ferrocene injection. However, a shift in the performance of the high speed rotor occurred, which may have an adverse effect on engine rejection ratio.

4. The TF41-A-2A engine did not meet model acceptance performance criteria upon completion of ferrocene/performance tests. The engine sustained numerous shifts in operating parameters.

5. Ferrocene does not appear to have any detrimental effects on the environs around the test cell.

6. The results of these individual engine tests indicate that ferrocene may be useful in controlling test cell exhaust smoke caused by J52-P-6B, J57-P-10 and J79-GE-8D engine during post-overhaul performance check runs.

RECOMMENDATIONS

1. The use of ferrocene should be considered for the control of test cell exhaust smoke caused by J52-P-6B, J57-P-10 and J79-GE-8D engines during post-overhaul performance check runs.

2. Long term effects of this smoke abatement additive on engines should be determined by monitoring the service performance of the first twelve engines of each model subjected to ferrocene during post-overhaul performance check runs.

3. Four additional TF30-P-6C engines should be tested using the ASAS and predissolved ferrocene combinations to document the magnitude of the high speed rotor performance shift and its possible impact on the engine rejection ratio for this engine.

4. The TF41-A-2A test using the ASAS and predissolved ferrocene combination should be repeated to confirm that the performance shifts were caused by ferrocene.

DESCRIPTION

1. Additive. Ferrocene, an organo-iron compound, was purchased from Arapahoe Chemicals, Boulder, Colorado in bulk 227 kilogram (kg) (500 pound) containers. Stock solutions of ferrocene were prepared by the NARF's employing JP-5 and toluene as solvents. Concentration values of 5 and 10 percent by weight of ferrocene in the solvents were the target concentrations; however, the lack of adequate weighing and mixing facilities at the NARF's resulted in significant deviation from these values.

2. Automated Smoke Abatement System. An ASAS manufactured by the Robert H. Wager Company, Incorporated, Chatham, New Jersey was used to control the additive flow rate and monitor the test cell exhaust plume opacity. The ASAS contains the following components: (a) a transmissometer, (b) a logic/control unit and (c) a gear pump attached to a variable speed motor. A schematic of this system is presented in figure (1). In this system the flow rate of the additive injected into the engine fuel system is regulated by the speed of the pump motor. This system operates in the following manner: The transmissometer measures the opacity of the test cell exhaust plume. In the logic/control unit, the transmissometer signal is compared to a reference signal. The logic/control unit, by regulating the speed of the pump motor, can increase, decrease or maintain the additive injection rate as required to hold the transmissometer and reference signals equal. The reference signal can be adjusted so that the exhaust stack plume opacity can be regulated to meet any local smoke opacity standard. Reference 4 is a comprehensive report on its development and evaluation for test cell use.

3. Engines. The following engines were employed in this ferrocene study:

Turbojet	Turbofan
J52-P-6B (S/N 649859)	TF30-P-6C (S/N 658342)
J57-P-10 (S/N 627207)	TF41-A-2A (S/N 141479)
J79-GE-8D (S/N 401801)	

These engines were newly overhauled and met the performance criteria for that engine model.

4. Environmental Test. Appendices A, B and C provide descriptions of the High Volume Stack Sampler, the Automatic Jet Engine Particulate Sampler, Tenax hydrocarbon adsorption tubes, cryogenic sampler system and a Beckman Model No. 402 Flame Ionization Detector employed during the particle size distribution, total particulate mass emission, and hydrocarbon species identification measurements conducted during the various engine tests.

METHOD OF TEST

1. Engine Evaluation.

a. Calibration of Automated Smoke Abatement System -

(1) Correlation of Transmissometer and Visual Opacity Measurements - Before the ASAS could be employed, it was necessary to establish a correlation between the transmissometer readings and the visually determined plume opacities. In this step, the test engine was operated at various power conditions between idle and military power rating to provide a broad spectrum of plume opacities. At each power condition, determinations of visual opacity of the smoke plume and the corresponding transmissometer reading were recorded.

(2) Calibration of the Logic/Control Unit - Once the correlation between the transmissometer and visual opacity was established, it was possible to determine the set point of the logic/control unit which would maintain the test cell smoke plume opacity within the 20 percent visual opacity limit established for the test program. In this calibration step, the test engine was maintained at the normal rated power rating and the set point from the logic/control unit was varied in a stepwise decreasing fashion. Each decrease in the set point caused a corresponding change in additive flow rate and plume opacity. Set point additive flow rate and plume opacity values were recorded.

b. Engine Performance Test - The set point on the logic/control unit was selected for a visual opacity of 20 percent which is the upper limit deemed acceptable by BAAPCD. The engine was operated between idle and military power ratings and the smoke level was monitored by the transmissometer and recorded by a strip chart recorder. During each engine test, a sample of the ferrocene stock solution was withdrawn and analyzed for its iron content by atomic absorption spectrophotometry as a check on the ferrocene concentration.

c. Engine Component Evaluation - Upon completion of the ferrocene test, the hot section of each engine was disassembled and inspected for deposit build-up. During the visual inspection, photographs were made of the hot section components to document their condition. A prior visual inspection and photographs had been made of each engine during its build-up after overhaul. In the case of the J79-GE-8D engine, a combustor can, fuel nozzle and two turbine blades were forwarded to the AFLC so they could make an independent visual inspection and do a metallurgical analysis of the deposit on those components.

d. Post-Ferrocene Evaluation - After the hot section inspection, each engine was reassembled and returned to the test cell. The engine performance calibration check run was repeated with regular JP-5 fuel without ferrocene. If the engine met the established performance criteria, the engine was made available for Fleet use. In phase two of this program, these engines will be monitored, while in service in the Fleet, to observe any long term effects of ferrocene.

2. Environmental Evaluation.

a. Particle Size Distribution and Particulate Mass Emissions - Samples of particulates were obtained at the engine exhaust exit plane and at the test cell exhaust stack exit using an Automatic Jet Engine Particulate Sampler

and a High Volume Stack Sampler respectively, while the test engine was operated at idle, normal rated and military power with and without ferrocene in the fuel. A detailed description of the procedures employed can be found in Appendix A.

b. Hydrocarbon Species Identification - The engine exhaust gases were sampled at the engine exhaust exit plane and at the test cell exhaust stack exit while the engine was operated at a moderate power setting, approximately 85 percent normal rated power, with and without ferrocene in the fuel. This condition was necessary because of the low concentration of hydrocarbons in the exhaust plume at higher power settings. At the engine exhaust exit plane, separate samples of the exhaust gas were analyzed by a Flame Ionization Detector, Tenax hydrocarbon adsorption tubes and a cryogenic sampler system. At the stack, only Tenax tubes and cryogenic sampler were employed. Samples of the hydrocarbons collected were sent to AFSAM for analysis by gas chromatographic and mass spectrometric techniques. Detailed descriptions of the procedures employed can be found in Appendices B and C.

DISCUSSION AND ANALYSIS OF RESULTS

1. Test Matrix. Table I presents a matrix showing the tests performed and the engines included in the test program. Those items marked with an "X" indicate the tests that were conducted on the various engines. Performance data, component inspection and test cell stack particulate measurements were conducted on all the engines included in the program. The full complement of environmental tests was performed only on the J57-P-10 and TF41-A-2A engines.

2. Engine Evaluation.

a. Automated Smoke Abatement System - The evaluation of the ASAS was conducted along with this engine test program. The system was capable of maintaining the test cell plume opacity to a visual opacity of 20 percent by injecting the minimum required concentration of ferrocene. Reference 4 fully describes the results of the correlation, calibration, and operation of this system during the test program and will not be repeated in this report.

b. Engine Performance Tests - The engine performance data obtained during the tests were evaluated by both NAPTC and NARF personnel. Table II contains data on test cell plume opacity without ferrocene, concentration of ferrocene to give a visual opacity of 20 percent, total test time, and time the engine was operated on ferrocene. A detailed analysis of the engine performance data obtained during the additive evaluations in these five engines is contained in Appendix D.

(1) J52-P-6B, J57-P-10 and J79-GE-8D Engines - Ferrocene caused no significant deterioration in the performance of the J52-P-6B, J57-P-10 and J79-GE-8D engines employed in this evaluation program. Based on these individual engine tests, the use of ferrocene appears to be an acceptable means of eliminating the test cell exhaust smoke plume caused by these three engines.

(2) TF30-P-6C - A decrease in the speed of the high speed rotor of the engine was observed when ferrocene was used. All other performance parameters monitored remained within the data scatter observed during the pre- and posttest calibration with additive free fuel. This performance change did not cause the engine to be rejected as the overall engine performance remained within the tolerance band allowed for this engine model. Additional data on the use of ferrocene during performance check-runs of other TF30-P-6C engines is necessary to fully document the high speed rotor performance decrease and its possible effect on the rejection ratio for this engine.

(3) TF41-A-2A - The TF41-A-2A engine experienced the most and largest shifts in engine performance parameters monitored. At the completion of the 10.8 hour test, this engine failed to meet the minimum acceptance performance criteria employed by the NARF in determining suitability of the engine for Fleet use. The TF41-A-2A was the first engine tested in the program and a number of program start-up problems were encountered. First, the transmissometer which drives the ASAS failed due to a loose wire in the receiver unit on the test cell stack. This problem was solved and corrected at the end of the test by epoxying all the wires in the source and receiver units on the test cell stack. Therefore, it was necessary to send a false transmissometer signal to the ASAS during this engine test to control the ferrocene flow rate. In addition, the flowmeter which was to monitor the total flow (fuel plus ferrocene solution) into the engine was not in place. This total flow flowmeter was installed in the system upon completion of this engine test. Normally, it would be acceptable to calculate the sum of the independent measurements of fuel flow rate and additive flow rate. Because of the need to trouble shoot the problem with the tran-missometer, the additive flow rate was not measured continuously. An average flow rate was used in the analysis of the engine data. It is esti-mated that this may account for a 2-5 percent error in fuel flow. Because of this problem, it is not possible to identify ferrocene as the complete cause of the performance shifts observed in this engine when it was operated on the smoke abatement additive. Posttest calibration of the engine on additive free fuel was not made because of a vibration problem that developed with this engine following reassembly after the visual inspection. Additional testing of this engine model is required to verify that the performance shifts occur with the use of ferrocene in the fuel.

c. Engine Component Evaluation - Operating the engines with ferrocene resulted in red deposits (iron oxide) on the hot-section components in varying degrees of thickness. In most instances, the red deposits were easily wiped off from the hot section component. There was no visible damage to components noted during the hot section inspection of the five engines, and the iron oxide deposits do not appear likely to interfere with normal operation of the engine. A detailed report on each engine hot section inspection can be found in Appendix D. Components from the hot section of the J79-GE-8D engine were provided to the Air Firce for their independent analysis. In addition to their visual inspection they also performed a metallurgical analysis on the deposits they observed. The Air Force concluded that the reddish deposit was iron oxide and that there was no penetration of the iron oxide through high temperature

protective coatings applied by the engine manufacturer. Appendix E contains the Air Force evaluation of the J79-GE-8D components.

d. Long Term Evaluation - Although the long term evaluation of the effects of ferrocene on engines is not included as part of the objective of this report, it must be taken into consideration when determining the total impact on Fleet readiness with the use of this smoke abatement technique. The second phase of this program involves monitoring those engines included in the extended use of ferrocene test with the exception of the TF30-P-6C and the TF41-A-2A engines to determine the effects of ferrocene on time between overhauls. Four additional J79-GE-8D engines have been subjected to ferrocene by NARF North Island and will be included in the phase two evaluation. One of the difficulties with the phase two evaluation is that it will take an excessive period of time to achieve the engine operating hours necessary to establish long term effects. As an example, the J79-GE-8D engine tested during December 1976 has, in the past nine months, been operated only 59 hours. At this rate it will take years before this engine receives a hot section inspection in which its condition can be observed by NARF and NAPTC personnel. One way of speeding up the phase two program would be by dedicating an engine of each model to be included in a simulated mission endurance test (SMET). In a SMET program, this information would be obtained in a couple of months. A SMET program for one engine in a sea level test cell at NAPTC would cost approximately $250,000. Before going the SMET route, a trade-off decision has to be made between the urgency of having long term evaluation data and the resources available for obtaining long-term evaluation data.

e. Summary - The overall assessment of the engine test program and recommendations for the continued evaluation of ferrocene for test cell smoke abatement are summarized in Table III. The J52-P-6B, J57-P-10 and J79-GE-8D engines appear to be capable of operating with ferrocene in the fuel during NARF check-out without any adverse affects on the engines. The first twelve engines should be monitored while in service to determine if there are any long term effects caused by ferrocene. At least four additional TF30-P-6C engine tests should be performed to document the high speed rotor shift and its possible effect on NARF engine rejection ratio. If these four additional engines also meet the minimum engine performance criteria they should be issued to the Fleet and monitored to determine if long term effects exist. The TF41 engine test should be repeated and this new test should establish whether excessive engine performance shifts do occur with the use of ferrocene.

3. Environmental Evaluation.

a. Particulate Mass Emissions - The techniques for sampling particulates from jet engine and test cell exhaust plumes are still evolving. AESO, as part of the particulate sampling phase, was evaluating a rapid high volume sampler which was developed specifically for jet engine exhaust plumes. This instrument reflects the best state-of-the-art technology for jet engine plume sampling. Three of the engines (J52-P-6B, J57-P-10 and TF30-P-6C) showed an approximate 50 percent reduction in particulate mass

emission when tested with this system. The J79-GE-8D and TF41-A-2A engines data show power conditions where ferrocene reduced mass emissions and other power conditions where it increased particulate mass emissions. Detailed analyses of these tests can be found in Appendix A. References 7 and 8 report the results of two separate particulate measurement programs on a J57-P-8B engine during which the effects of ferrocene on particulates were measured. In both tests ferrocene reduced particulate mass emissions approximately 50 percent.

b. Particle Size Distribution - The size distribution data contain a number of inconsistencies in the results obtained for the different power conditions tested for a given engine, and a large variation in size distribution for the engines tested. It is impossible to determine absolute ferrocene effects on size distribution with the data obtained in these tests. The only trend that seems to be consistent throughout the data is that ferrocene reduces the number of particles with diameters of 0.03 mm or less. Appendix A describes these results in more detail.

c. Hydrocarbon Species Identification - Determining the significance of the data was extremely difficult due to the small quantities of specific hydrocarbons in the jet engine exhaust plume. An overview of all the concentration data and their scatter indicates that ferrocene does not affect the concentration of unburned hydrocarbons in the exhaust plume. Further analysis was attempted on samples of hydrocarbons which were condensed out of the exhaust plume. A large number (47 for regular JP-5 and 70 for ferrocene/JP-5) of specific compounds were identified but their concentrations were too small to provide consistent results. The only trend noted was that all of the samples from tests employing ferrocene contained higher levels of aldehydes and ketones than existed in samples obtained when ferrocene was not used. Further discussion of the hydrocarbon species identification analysis can be found in Appendices B and C.

d. Additional Available Information (reference 1) -

(1) Gaseous Emissions - During an earlier T56 engine test, a special effort was made to measure the effects of ferrocene on gaseous emissions. At a concentration of 305 μg (iron)/g (fuel), the unburned hydrocarbons and carbon monoxide increased by approximately 30 percent over base line values for all engine power ratings tested while oxides of nitrogen decreased about 8 percent. In a separate test conducted at NARF Alameda on a J52-P-6B engine at a concentration of 200 μg (iron)/g (fuel) an average increase of 11 percent in CO was observed while the other gaseous emissions remained unchanged.

(2) Other Exhaust Products - The question of the existence of iron carbonyl in the test cell exhaust gases has been mentioned. The Naval Research Laboratory reported, that even under the most "ideal" conditions the concentration of iron pentacarbonyl would never exceed 1×10^{-19} parts per million and that the concentration would most likely be much lower because the conditions which exist in jet engine test cell exhaust systems are far from ideal. The presence of oxygen, carbon dioxide, oxidizing gases (NO_x), sunlight, iron oxide film and high temperature retard the formation of iron pentacarbonyl. All of the above

are inherent in the jet engine test cell exhaust system.

(3) Toxicity of Ferrocene - The results of ocular irritation studies indicate that the ferrocene alone and in the solvents caused very little, if any, ocular irritation. Dermal irritation studies were negative. Acute inhalation studies with ferrocene dust showed no significant toxic symptoms. Acute exposures to ferrocene along with the individual solvents showed no increase in toxicity over that of the solvent alone. The oral and intraperitoneal LD_{50} for ferrocene placed it in the category of "slightly toxic". These studies indicate that ferrocene will not present an occupational health hazard if used at NARF's.

e. Summary - Other than the cosmetic effect of reduced smoke, ferrocene did not significantly alter the concentrations and type of pollutants in the test cell exhaust plume from those present when the engine was operated on JP-5 fuel without ferrocene. The use of ferrocene does not present a threat to NARF personnel who will have to handle this material nor does it cause a significant change to the environs surrounding the test cell.

4. Ferrocene Stock Solution. Table II presents the analysis of the ferrocene concentration in the stock solutions employed during this test program. The concentration of ferrocene in the stock solutions made at the NARF's varied from test to test because of problems encountered in measuring small quantities (4.54 kg (10 pounds)) of ferrocene from a 227 kg (500 pound) bulk container of the additive without the use of a scale. It was realized from the beginning that the NARF's were not equipped to make stock solutions for routine use of ferrocene. Reference 1 recommended that ferrocene be purchased predissolved in a solvent. From the solvents recommended by NAPTC, the Bureau of Medicine and Surgery has selected xylene as the best solvent from a hazard and toxicity standpoint. If additional testing is performed or use of the additive is initiated, consideration should be given to the purchase of ferrocene dissolved in xylene. Arapahoe Chemicals Incorporated, Boulder, Colorado, has stated in reference 9 that they are willing to supply this material at a cost of \$3.22/kg (\$1.46/pound) in drum quantities with discounts for large purchases. The use of the predissolved material has many advantages, three of the most important of which are: (a) quality control (all the NARF's/NAS's would be using same material), (b) test cell operational personnel would not be required to make the stock solution and, and (c) the material could be made available from GSA supply.

FIGURE I. AUTOMATED SMOKE ABATEMENT SYSTEM

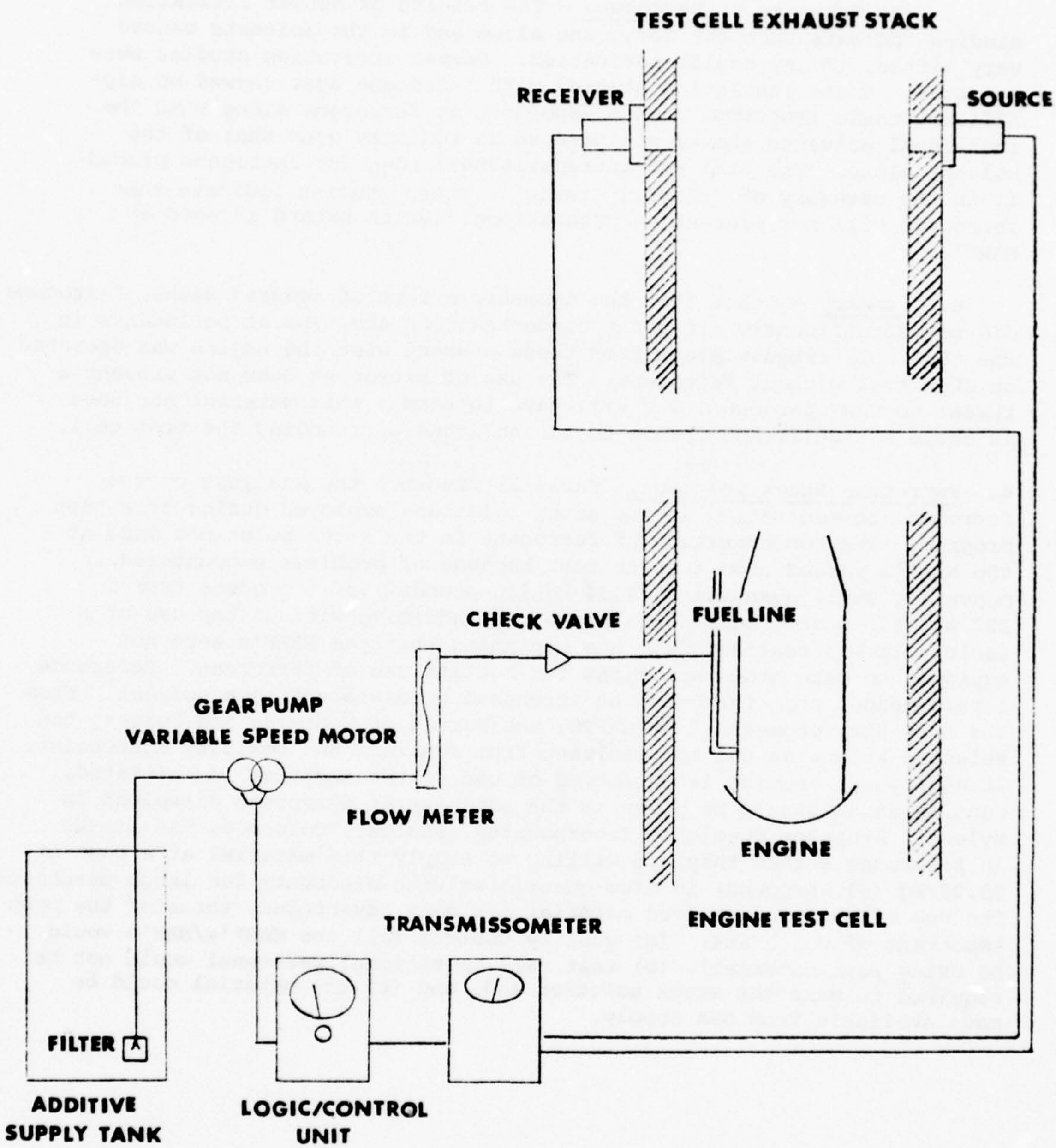


TABLE I

TEST MATRIX

Tests

Engine	Performance Data	Component Inspection	Metallurgical Analysis	Particulates Engine	Particulates Stack	Hydrocarbons Engine	Hydrocarbons Stack
J52-P-6B	X	X			X		
J57-P-10	X	X		X	X	X	X
J79-GE-8D	X	X	X		X		
TF30-P-6C	X	X		X	X		
TF41-A-2A	X	X		X	X	X	X

TABLE II

SUMMARY ENGINE PERFORMANCE TEST

Engine	Visual Plume Opacity (no ferrocene) Ringlemann No.	Visual Plume Opacity (no ferrocene) Percent	Ferrocene Concentration In Fuel,[1] weight %	Operating Time with Ferrocene, (hours)	Total Operating Time (hours)	Stock Solution Concentration, weight % ferrocene
J52-P-6B	2.5	50	0.063	8.0	10.4	6.9[2]
J57-P-10	1.75[3]	35[3]	0.021	8.2	12.0	2.4
J79-GE-8D	2.5	50	0.074	8.6	10.5	4.7
TF30-P-6C	2.75	55	0.083	7.9	11.7	7.7[2]
TF41-A-2A	2.0	40	0.035	8.2	10.8	2.7

NOTES: 1 - Concentration required to give 20 percent visual opacity when test engine is at military rating.

2 - Ferrocene stock solution was made with toluene only. JP-5 was not used as a solvent for ferrocene.

3 - Opacity reading not made on this engine because tests were run at night. Opacity data were obtained from the Naval Air Propulsion Test Center Report No. NAPTC-LR-76-37 of 27 September 1976.

TABLE III

SUMMARY ENGINE EVALUATION

Engine	Effect on Performance	Visual Inspection	Overall Assessment	Recommendation
J52-P-6B	Negligible	No serious deposits identified.	Satis-factory	Use ferrocene. Monitor first 12 engines in service to determine if long term effects exist.
J57-P-10	Negligible	No serious deposits identified.	Satis-factory	Use ferrocene. Monitor first 12 engines in service to determine if long term effects exist.
J79-GE-8D	Negligible	No serious deposits identified.	Satis-factory	Use ferrocene. Monitor first 12 engines in service to determine if long term effects exist.
TF30-P-6C	Minor	No serious deposits identified.	Satisfac-tory with reserva-tions.	Test four additional engines to confirm magnitude of shift and its effect on engine rejection ratio.
TF41-A-2A	Significant	No serious deposits identified.	Unsatis-factory with questions.	Retest to ascertain performance shifts.

REFERENCES

1. REPORT: Naval Air Propulsion Test Center Report No. NAPTC-PE-103, "Evaluation of Smoke Suppressant Fuel Additives for Jet Engine Test Cell Smoke Abatement", A. F. Klarman, February, 1977

2. LETTER: Naval Air Systems Command letter AIR-4147A:CSS of 3 July 1973

3. LETTER: Naval Air Systems Command letter AIR-4147A:CSS of 24 June 1974

4. REPORT: Naval Air Propulsion Test Center Report No. NAPTC-PE-108, "Evaluation of an Automated Smoke Abatement System for Jet Engine Test Cells", A. F. Klarman, July, 1977

5. MEETING: Environmental Work Shop Conference - California's Suit Against the Navy - Effect on Jet Engine Test Cell Operations, 9-10 February 1976, NAVFAC (WESTDIV), San Bruno, California

6. AUTHORIZATION: NAVAIR Work Unit Assignment No. NAPTC-OP7-426 dated 19 July 1976

7. REPORT: Naval Air Propulsion Test Center Letter Report No. NAPTC-LR-76-8, "Evaluation of a Sampling Train Procedure for Measuring Gas Turbine Engine Particulates", A. F. Klarman, J. E. Horling of 30 April 1976

8. REPORT: Coordinating Research Council, Inc. Report No. CRC 491, "1973 CRC Aircraft Engine Exhaust Particulate Measurement Tests" March, 1977.

9. LETTER: Arapahoe Chemicals Inc. letter JJK/jn of 16 September 1977

APPENDIX A

PARTICULATE EMISSIONS FROM J79, J52, J57, TF30 AND TF41 ENGINES DURING TEST CELL FERROCENE EVALUATIONS

REPORT NO. AESO 111-77-2
FEBRUARY 1977

PARTICULATE EMISSIONS FROM J79, J52, J57, TF30, AND TF41 ENGINES DURING TEST CELL FERROCENE EVALUATIONS

NAVAL ENVIRONMENTAL PROTECTION SUPPORT SERVICE
NAVAL AIR SYSTEMS COMMAND
AIRCRAFT ENVIRONMENTAL SUPPORT OFFICE
NAVAL AIR REWORK FACILITY
SAN DIEGO, CALIFORNIA 92135

Enclosure (1)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont)

LIST OF TABLES

LIST OF ABBREVIATIONS

AESO	Aircraft Environmental Support Office
EPA	Environmental Protection Agency
NAVAIRPROPTESTCEN	Naval Air Propulsion Test Center
NAVAIREWORKFAC	Naval Air Rework Facility
RPM	Revolutions Per Minute
USAFSAM	United States Air Force School of Aerospace Medicine

I. INTRODUCTION

A. Special tests to determine the effect of ferrocene-containing fuel on the operational characteristics and the components of gas turbine engines were initiated at NAVAIREWORKFAC, North Island on 8 November 1976, and at NAVIAREWORKFAC, Alameda on 29 November 1976. These tests were coordinated by the NAVAIRPROPTESTCEN. The main purpose of these tests was to evaluate the engine after 10-hour operations using ferrocene-containing fuel. In other testing, the AESO measured gaseous, smoke, and particulate emissions at NAVAIREWORKFAC, North Island and total hydrocarbons and particulate emissions at NAVAIREWORKFAC, Alameda. The USAFSAM collected hydrocarbon samples at NAVAIREWORKFAC, Alameda.

B. This report gives the results of the particulate emission measurements taken by the AESO at NAVAIREWORKFAC's, North Island and Alameda.

II. EXPERIMENTAL

A. Equipment

1. An Aerotherm High Volume Stack Sampler (HVSS) was used to take samples at the test cell stack exhaust plane. The HVSS allows samples of up to six cubic feet per minute to be taken while following EPA Method 5.

2. The Aerotherm Automatic Jet Engine Particulate Sampler was used to sample particulate emissions isokinetically at the engine exhaust plane. The mass loading samples were taken according to EPA Method 5. The sampler takes particle size distributions using a Thermo Systems Model 3030 Electrical Aerosol Analyzer simultaneously with total particle loading. The Model 3030 was detached from the automatic sampler and used to take the top of stack size distributions.

B. Sampling Procedure

1. Top of Stack

a. The stacks for the test cells at NAVAIREWORKFAC, North Island and Alameda are externally identical. They are 60 feet high and 22 feet square with one-foot thick walls. Both stacks contain sound baffles to reduce the emission of noise. At NAVAIREWORKFAC, North Island these sound baffles are at the stack rim. At NAVAIREWORKFAC, Alameda the sound baffles are approximately 10 feet below the stack rim.

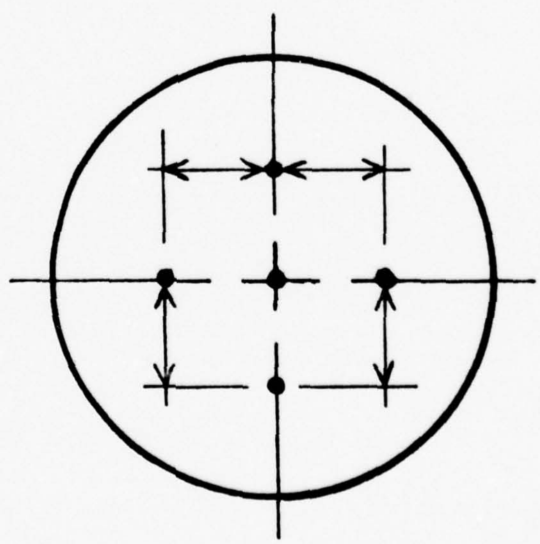
b. The placement of the sound baffles produced two distinct flow regimes which required two separate sample traverse schemes. At

NAVAIREWORKFAC, North Island a five-point traverse was used. The points were chosen to represent the widely varying exit velocities across the baffles. Each point was sampled for three minutes. At NAVAIREWORKFAC, Alameda the flow was divided into two regimes. The upstream (west) side of the stack showed exit velocities from -2 to +2 feet per second (fps). The downstream (east) side of the stack showed much higher velocities from 30 to 50 fps in an almost homogeneous flow. The flow pattern plus sample platform physical limitations, limited traversing to three points for five minutes each. The three points were taken at nine, six, and three feet from the east wall of the stack approximately eight feet from the south wall.

2. Engine Exhaust Plane

The gas turbine engine exhausts are circular and vary from 12 to 30 inches in diameter. For each engine mode, a total of five traverse points were sampled (Figure 1). Each point was sampled for three minutes.

FIGURE 1



Engine Exhaust Plane Traverse Points
All indicated distances are one-quarter diameter.

C. Collection and Analysis of Data

1. The J79 engine was sampled at NAVAIREWORKFAC, North Island on 6 November 1976, with ferrocene and 12 November 1976, without ferrocene. Samples were taken at the top of the stack only. Figures 2-6 give the size distribution of the particles emitted. Table I gives the results of the Method 5 samples.

TABLE I PARTICULATE EMISSIONS FROM A J79-GE-8D GAS TURBINE AT NAVAIREWORKFAC, NORTH ISLAND

Mode	Without Ferrocene		With Ferrocene	
	mg/m^3	gr/scf	mg/m^3	gr/scf
Idle	11.2	0.0049	61.5*	0.0269
30% (thrust)	-		49.4	0.0216
85% (RPM)	31.7	0.0138	27.1	0.0118
Normal Rated	26.5	0.0116	20.5	0.0090
Military	27.1	0.0118	64.7	0.0282

*Ferrocene is not used at idle, but this data point was taken during the ferrocene run.

2. The J52-P-6B engine was sampled at NAVAIREWORKFAC, Alameda on 4 December 1976, and 15 January 1977. Samples taken on 15 January were size distribution and duplicate total mass emissions without ferrocene at the top of the stack. No engine exhaust plane samples were taken because of the excess probe to engine distance. Figures 7-9 give the size distribution of the particles emitted.

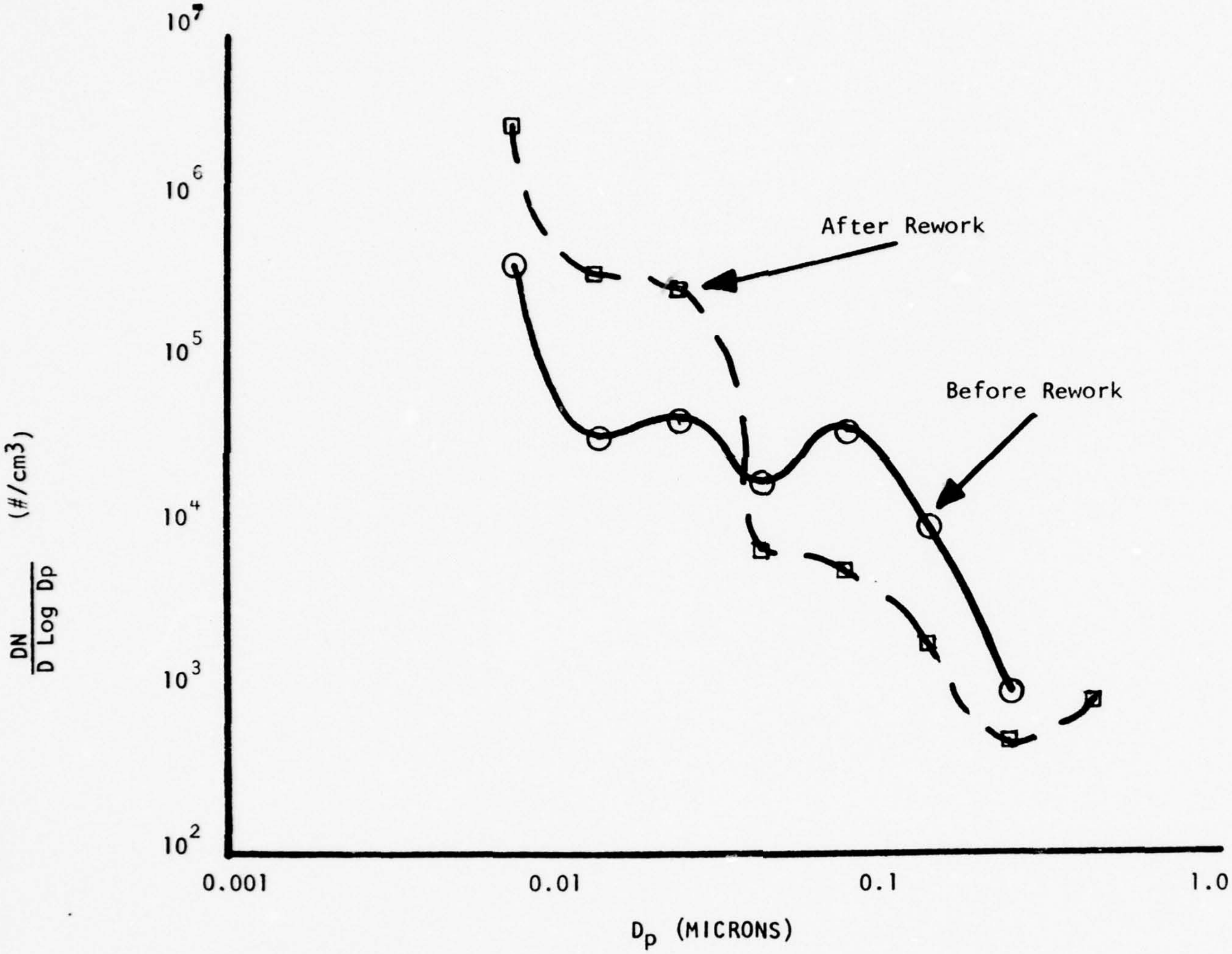


FIGURE 2

Size Distribution of Aerosol Emitted From Test Cell
By J79 Engine at Idle Power Before and After Ferrocene Test

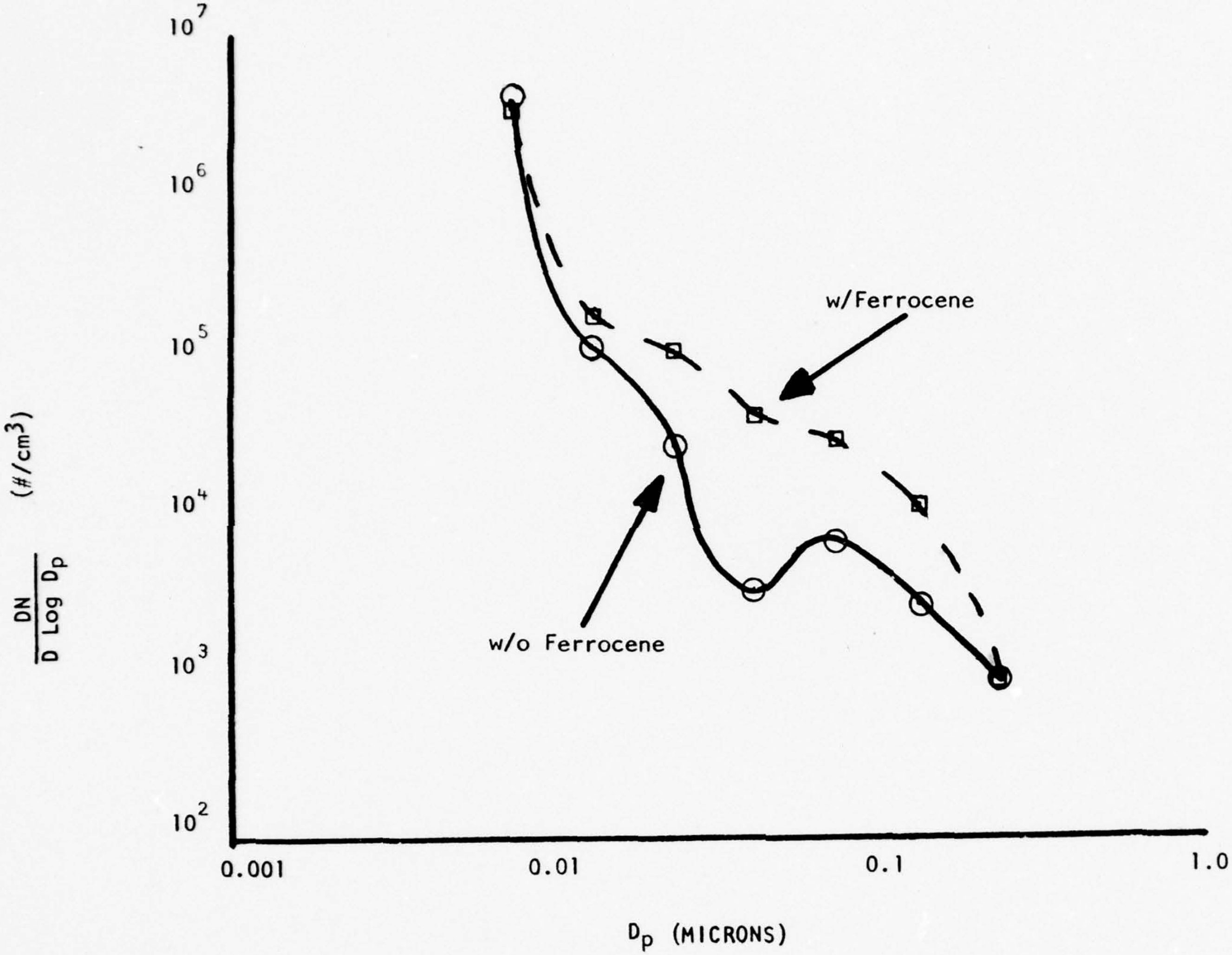


FIGURE 3

Size Distribution of Aerosol Emitted From Test Cell By J79 Engine
At 30% (Thrust) Power With and Without Ferrocene

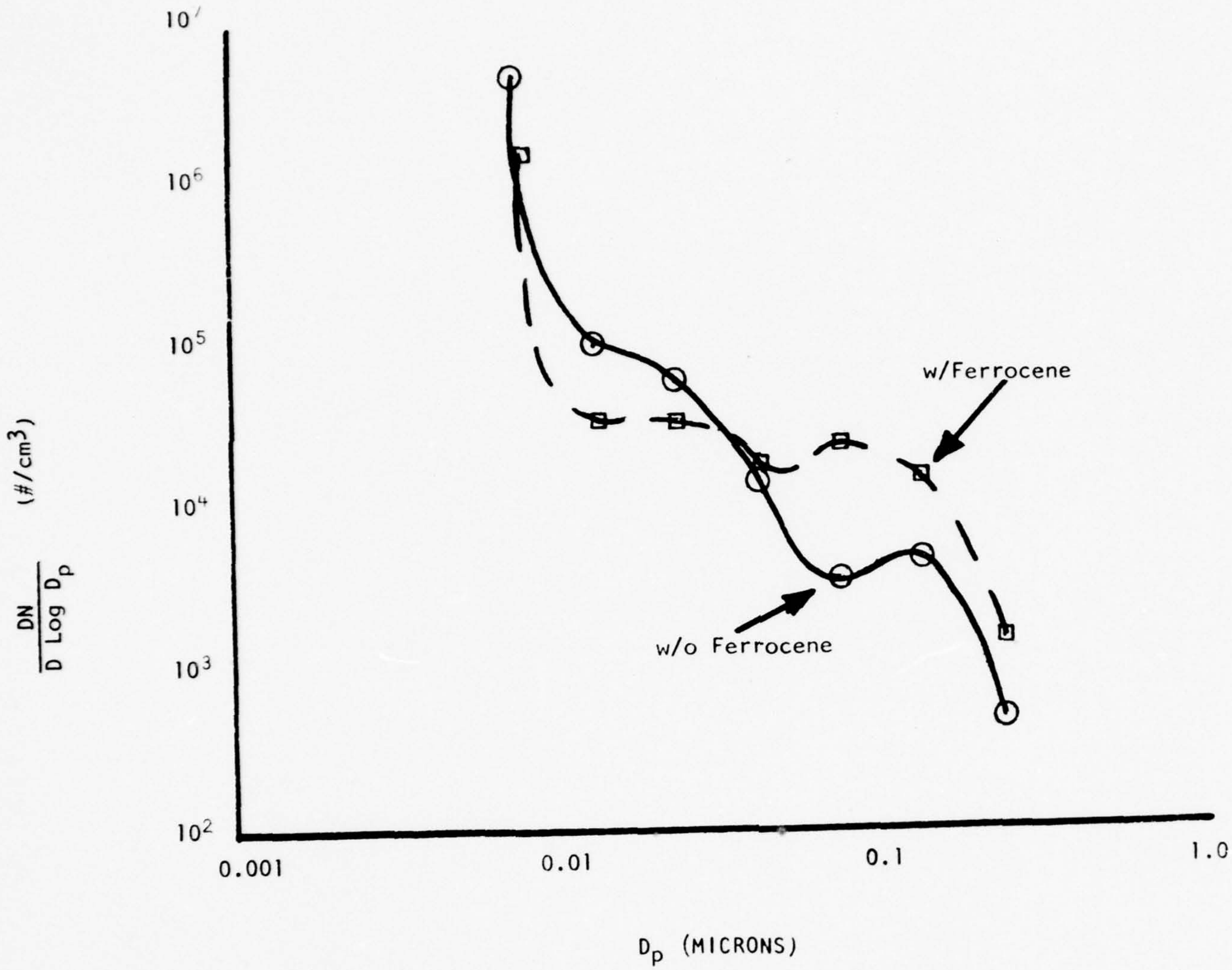


FIGURE 4

Size Distribution of Aerosol Emitted From Test By J79 Engine At 85% (RPM) Power With and Without Ferrocene

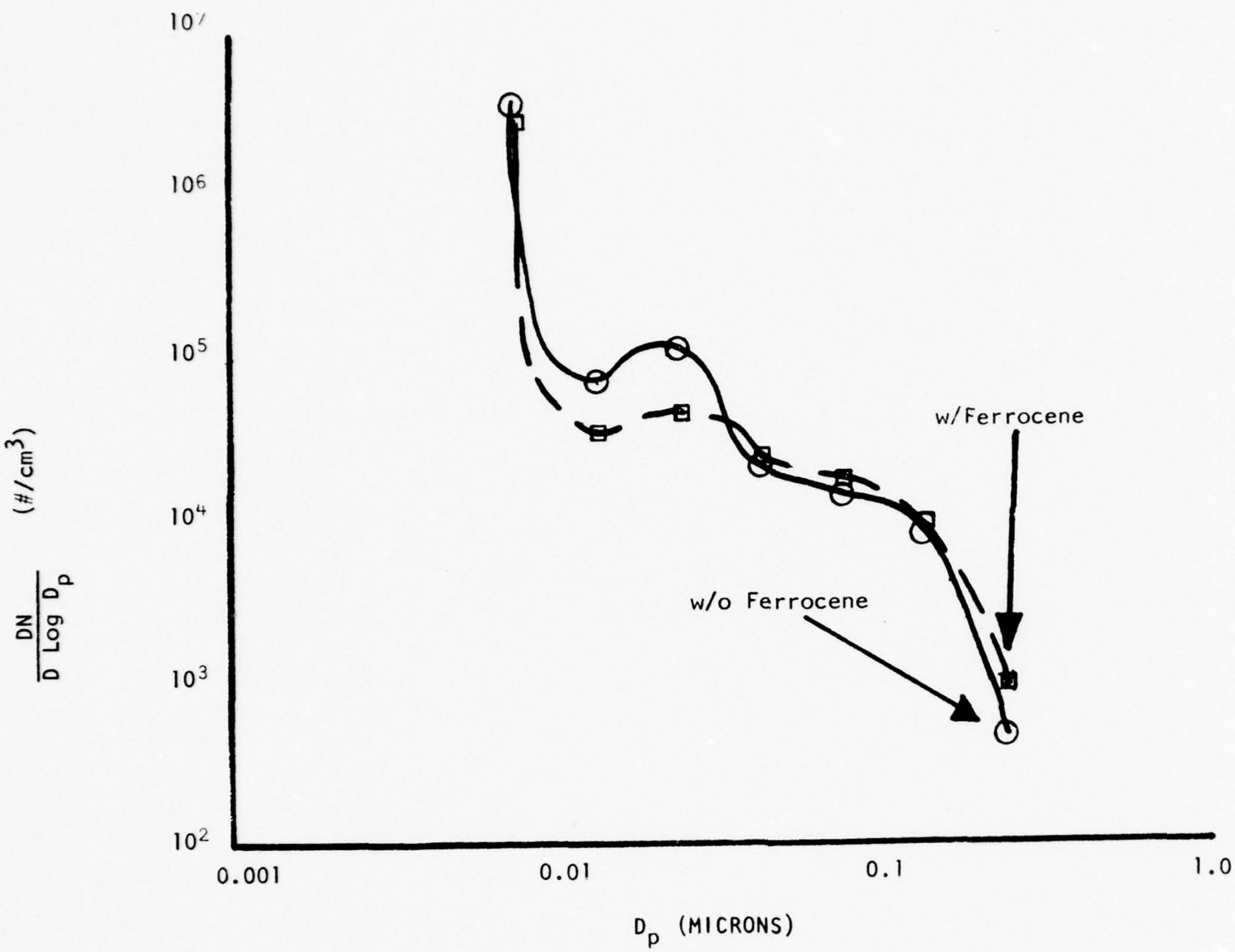


FIGURE 5

Size Distribution of Aerosol Emitted From Test Cell By J79 Engine
At Normal Power With and Without Ferrocene

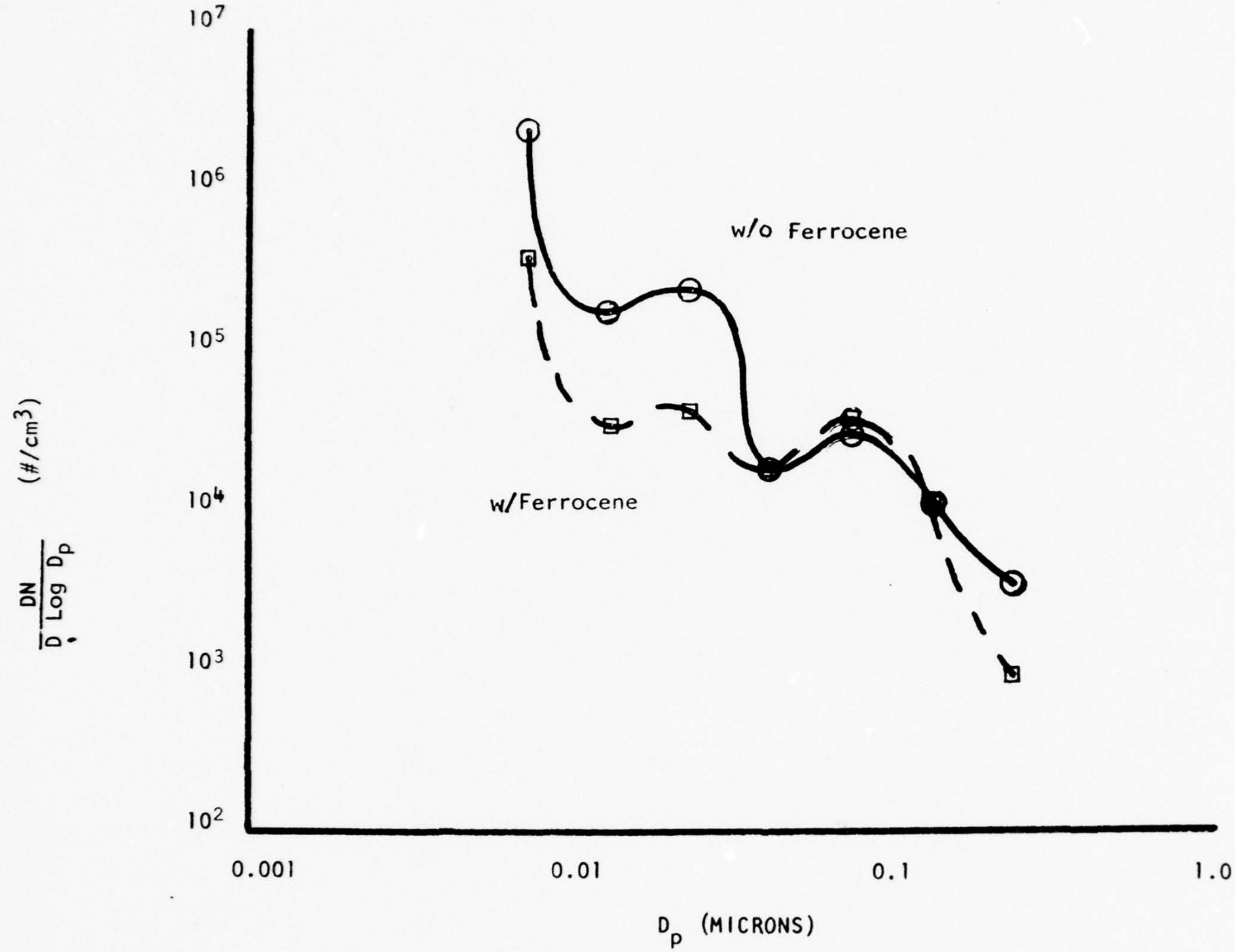


FIGURE 6

Size Distribution of Aerosol Emitted From Test Cell By J79 Engine At Military Power With and Without Ferrocene

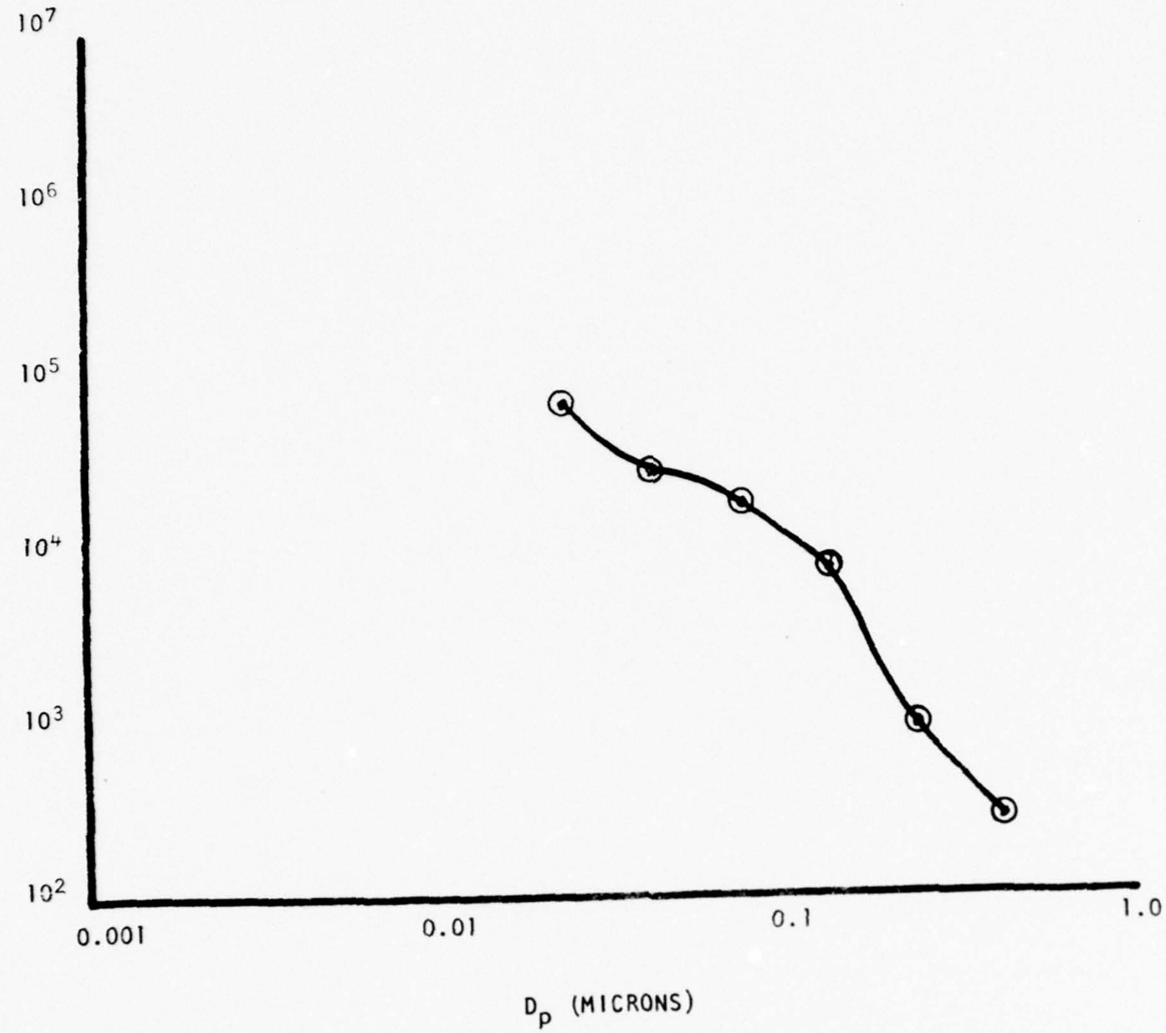


FIGURE 7

Size Distribution of Aerosol Emitted From Test Cell
By J52 Engine At Idle Power Without Ferrocene

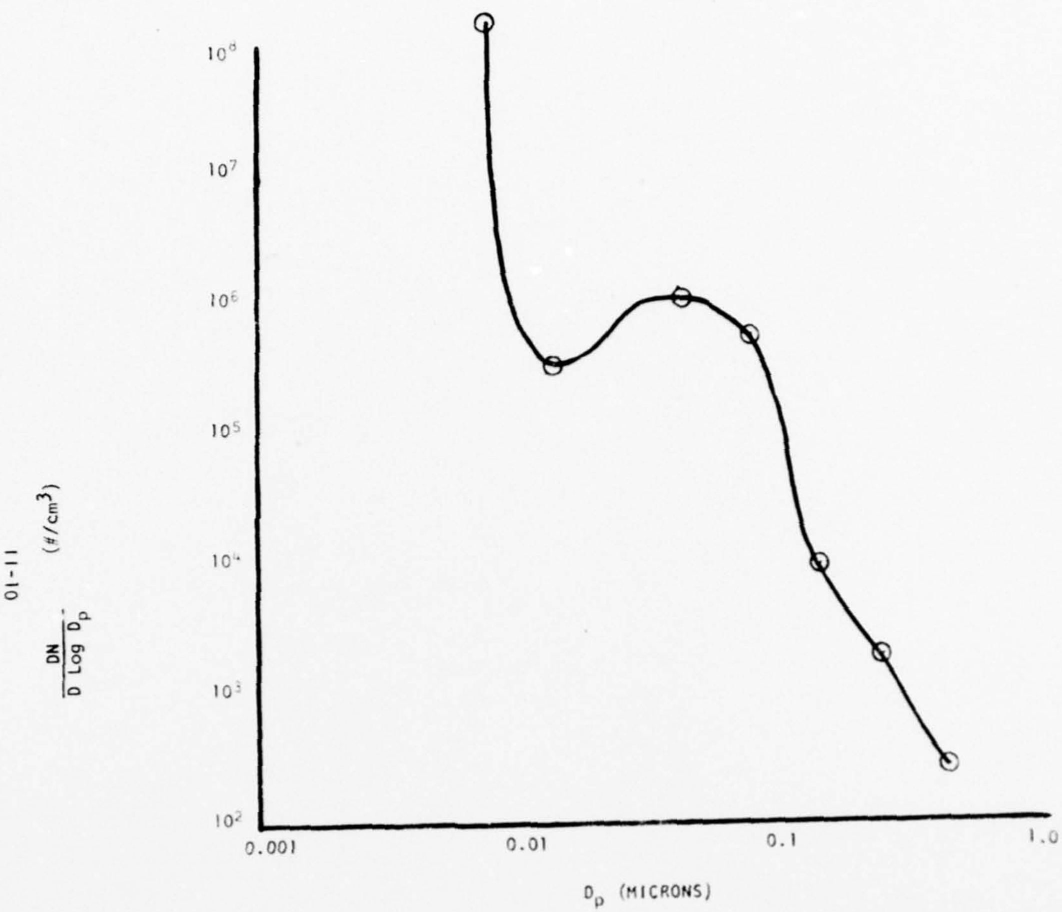


FIGURE 8

Size Distribution of Aerosol Emitted From Test Cell
By J52 Engine At Normal Rated Power Without Ferrocene

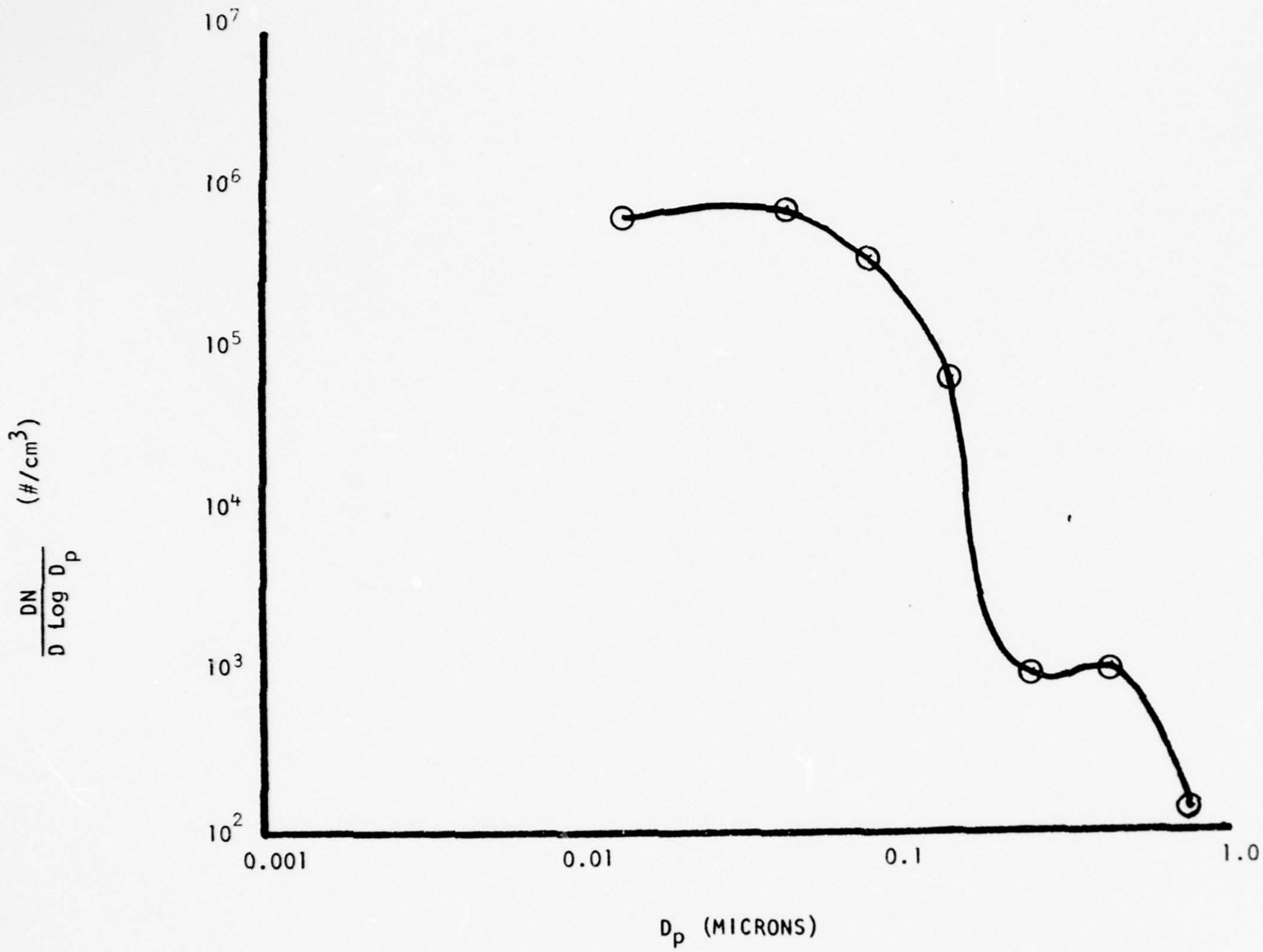


FIGURE 9

Size Distribution of *Aerosol* Emitted From Test Cell
By J52 Engine At Military Power Without Ferrocene

Table II gives the results of the Method 5 samples.

TABLE II PARTICULATE EMISSIONS FROM A J52-P-6B GAS TURBINE AT NAVAIREWORKFAC, ALAMEDA

Mode	Without Ferrocene		With Ferrocene	
	mg/m^3	gr/scf	mg/m^3	gr/scf
Idle	1.8	0.0008	-	-
Normal Rated	13.2	0.0058	3.5	0.0015
Military	11.0	0.0048	3.0	0.0013

3. The J57-P-10 engine was sampled at NAVAIREWORKFAC, Alameda on 3 December 1976, and 12 January 1977. Samples taken on 12 January 1977, were size distribution and duplicate total mass emissions without ferrocene at the top of the stack. Figures 10-14 give the size distribution of the particles emitted. Table III gives the results of the Method 5 samples.

TABLE III PARTICULATE EMISSIONS FROM A J57-P-10 GAS TURBINE AT NAVAIREWORKFAC, ALAMEDA

Mode	Engine Exhaust Plane W/O Ferrocene		Engine Exhaust Plane W/Ferrocene		Top of Stack W/O Ferrocene		Top of Stack W/Ferrocene	
	mg/m^3	gr/scf	mg/m^3	gr/scf	mg/m^3	gr/scf	mg/m^3	gr/scf
Idle	11.6	0.0051	-		5.2	0.0023	-	
Normal Rated	28.9	0.0126	10.9	0.0048	14.6	0.0064	9.3	0.0041
Military	25.4	0.0111	9.7	0.0042	21.8	0.0095	10.3	0.0045

4. The TF30-P-6C engine was sampled at NAVAIREWORKFAC, Alameda on 6 December 1976, and 14 January 1977. Samples taken on 14 January were size distribution and duplicate total mass samples at the top of the

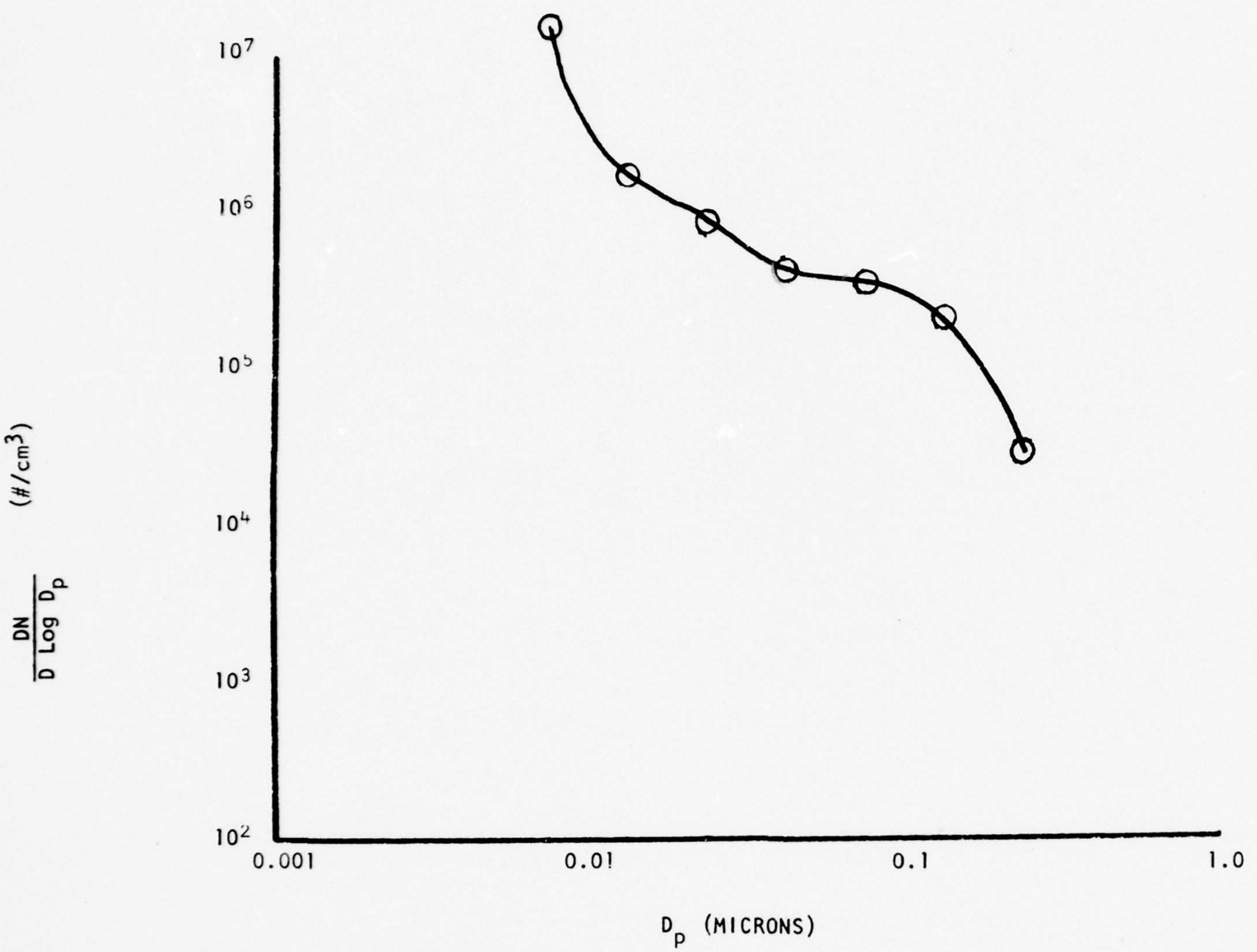


FIGURE 10

Size Distribution of AerosolEmitted From J57 Engine
At Idle Power Without Ferrocene

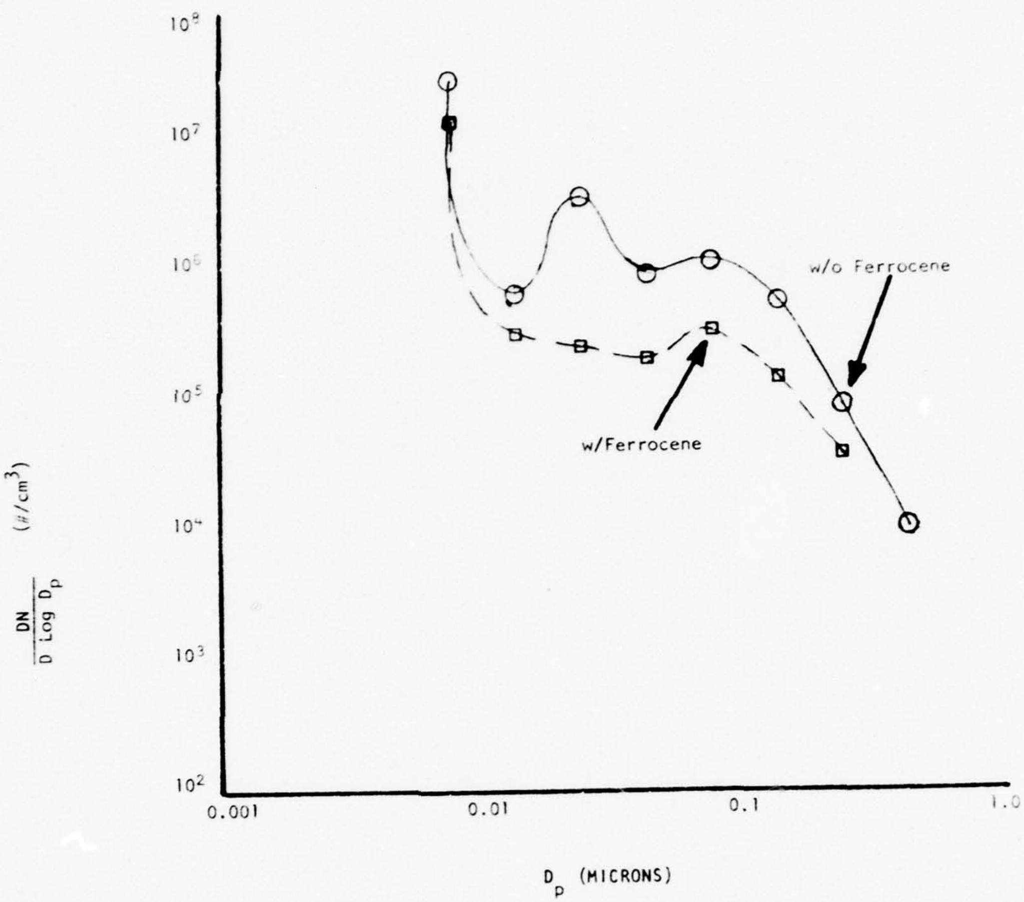


FIGURE 11

Size Distribution of Aerosol Emitted From J57 Engine
At Normal Rated Power With and Without Ferrocene

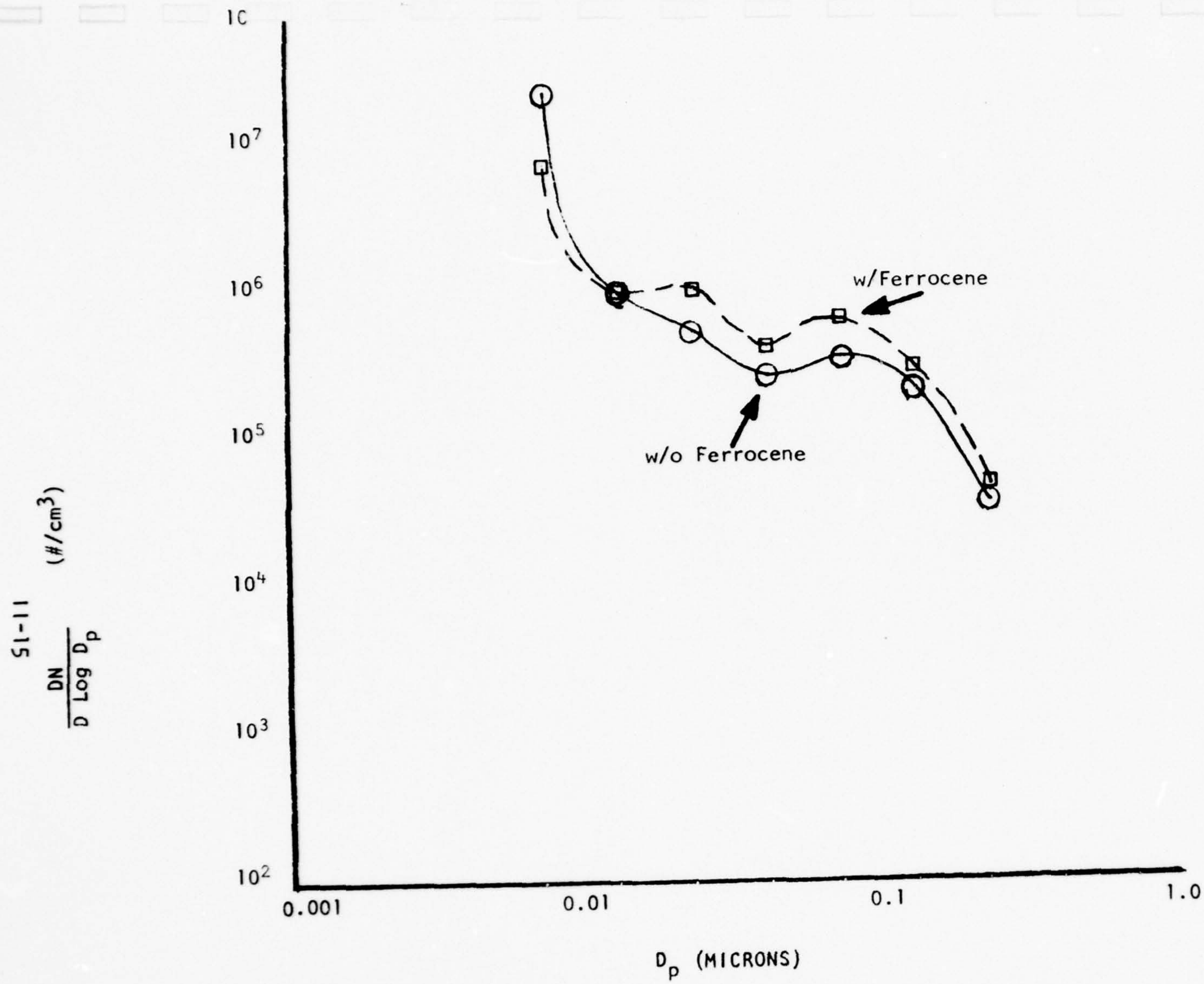


FIGURE 12

Size Distribution of Aerosol Emitted From J57 Engine
At Miliraty Power With and Without Ferrocene

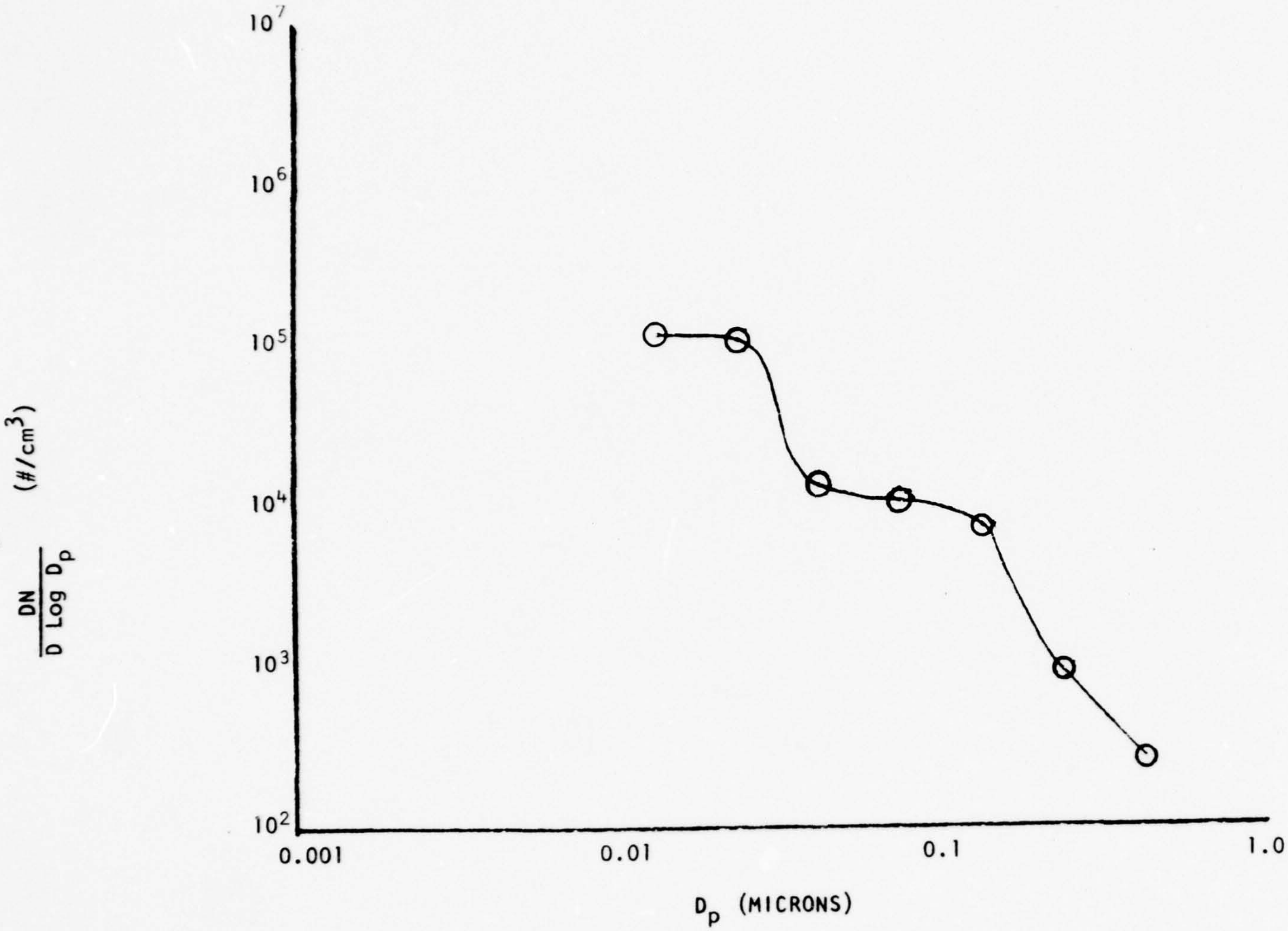


FIGURE 13

Size Distribution of Aerosol Emitted From Test Cell
By J57 Engine At Normal Rated Power Without Ferrocene

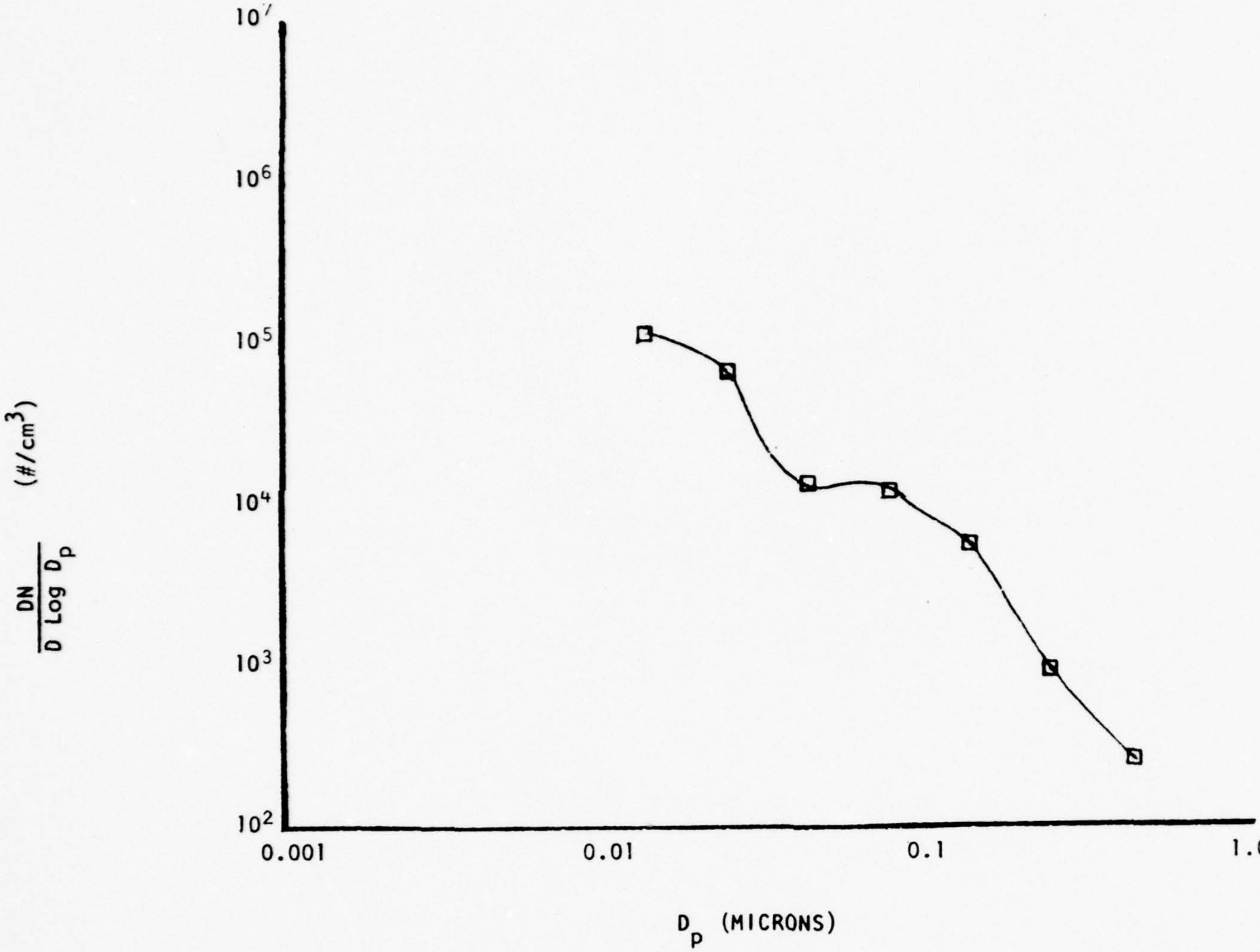


FIGURE 14

Size Distribution of Aerosol Emitted From Test Cell By J57
At Military Power Without Ferrocene

stack only. Figures 15-18 give the size distribution of the particles emitted. Table IV gives the results of the Method 5 samples.

TABLE IV PARTICULATE EMISSIONS FROM A TF30-P-6C GAS TURBINE ENGINE AT NAVAIREWORKFAC, ALAMEDA

Mode	Engine Exhaust Plane W/O Ferrocene		Engine Exhaust Plane W/Ferrocene		Top of Stack W/O Ferrocene		Top of Stack W/Ferrocene	
	mg/m^3	gr/scf	mg/m^3	gr/scf	mg/m^3	gr/scf	mg/m^3	gr/scf
Idle	13.3	0.0058	-	-	3.5	0.0015	-	-
Normal Rated	66.5	0.0290	32.5	0.0142	18.6	0.0081	8.6	0.0038
Military	76.8	0.0335	29.7	0.0130	28.7	0.0125	9.7	0.0042

5. The TF41-A-2 engine was sampled at NAVAIRWWORKFAC, Alameda on 1 and 2 December 1976, and 10 January 1977. Samples taken on 10 January were size distribution and duplicate total mass samples at the top of the stack only. Figures 19-21 give the measured size distribution of the particles emitted. Table V gives the results of the Method 5 samples.

TABLE V <u>PARTICULATE EMISSIONS FROM A TF41-A-2 GAS TURBINE ENGINE AT NAVAIREWORKFAC, ALAMEDA</u>

Mode	Engine Exhaust Plane W/O Ferrocene		Engine Exhaust Plane W/Ferrocene		Top of Stack W/O Ferrocene		Top of Stack W/Ferrocene	
	mg/m^3	gr/scf	mg/mg^3	gr/scf	mg/m^3	gr/scf	mg/m^3	gr/scf
Idle	53.0	0.0231	-	-	4.8	0.0021	-	-
Normal Rated	-	-	21.1	0.0092	21.7	0.0095	5.1	0.0022
Military	-	-	20.5	0.0090	12.4	0.0054	32.4	0.0142

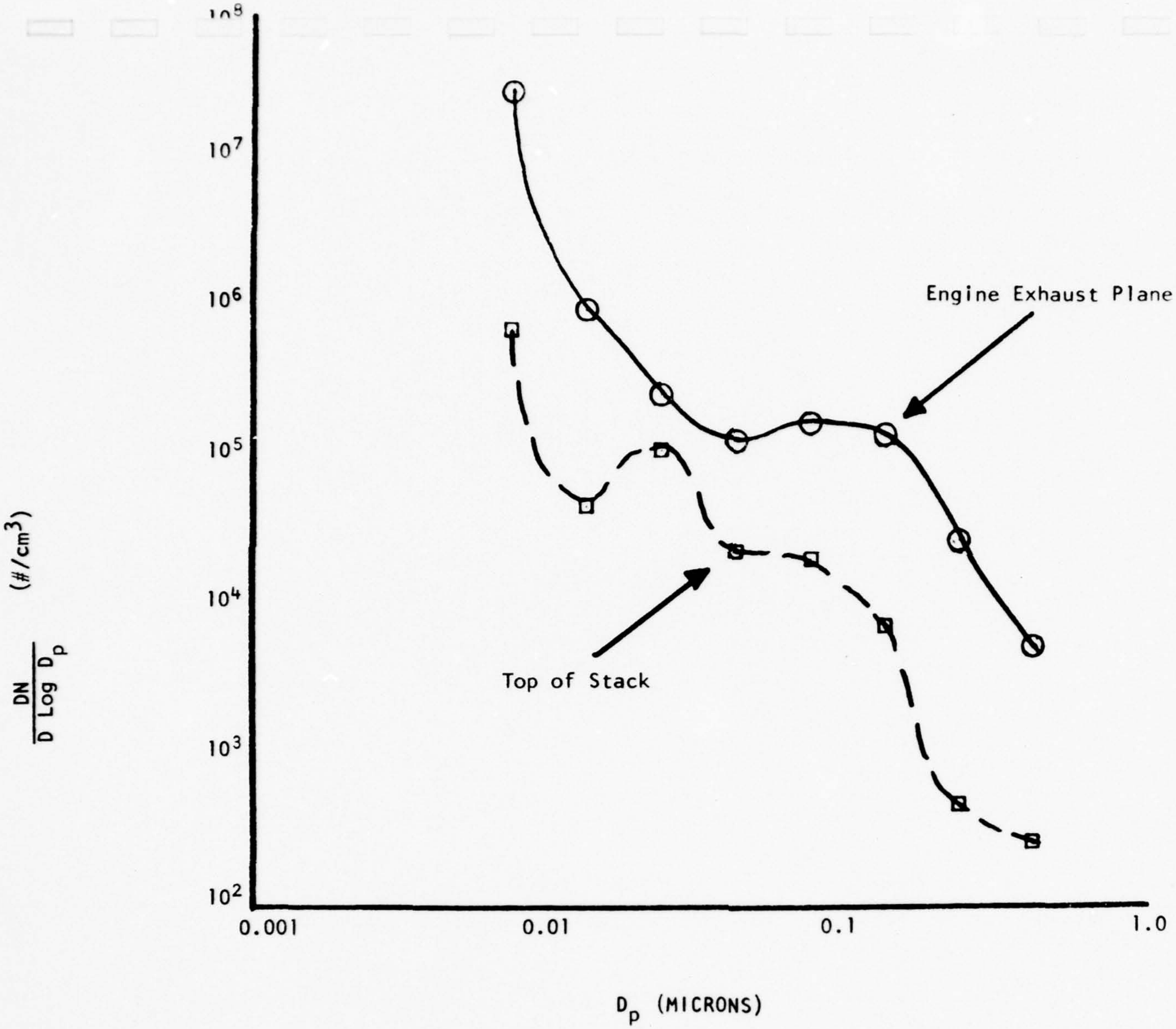


FIGURE 15

Size Distribution of Aerosol Emitted From Test Cell Stack and TF30 Engine at Idle Power Without Ferrocene

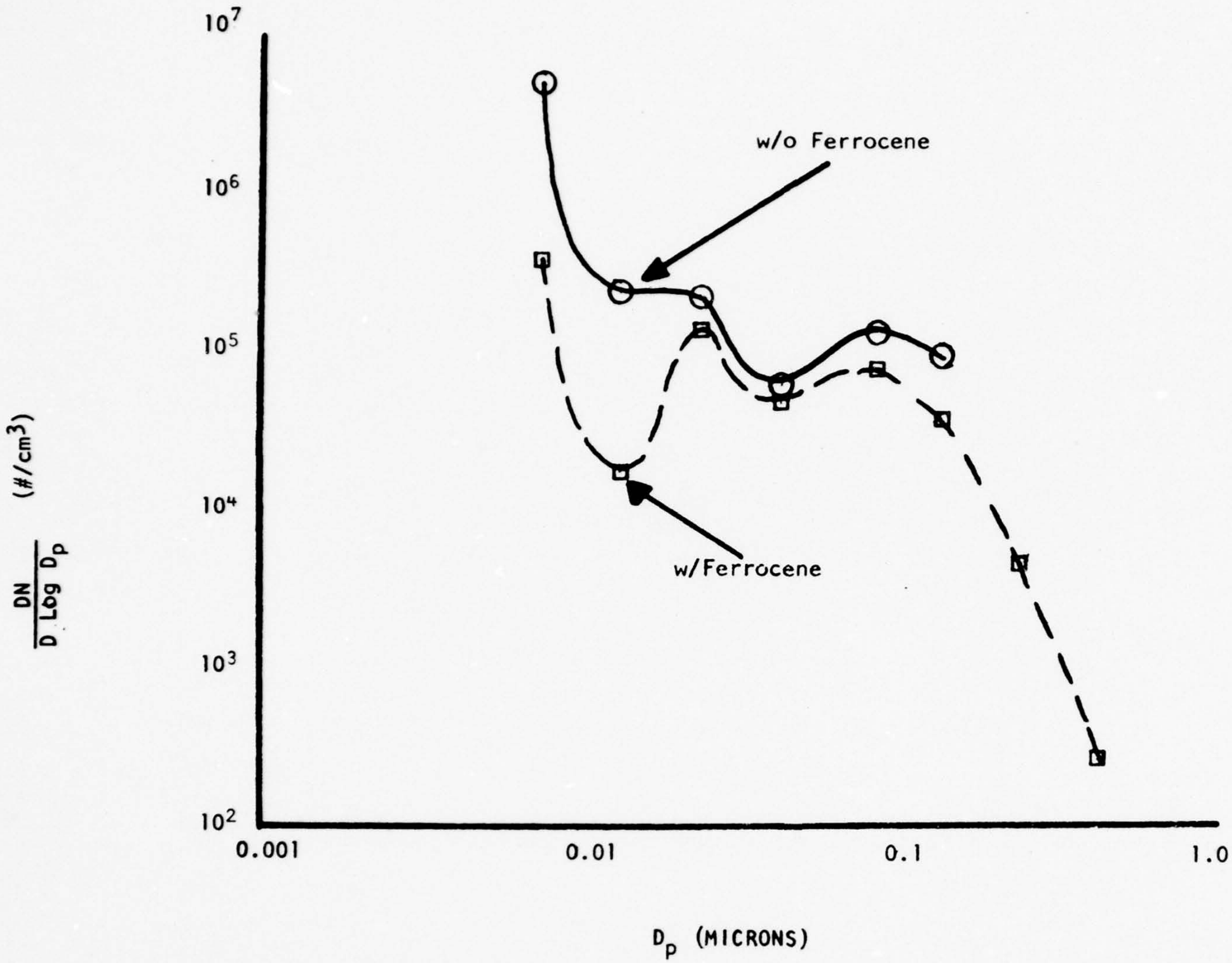


FIGURE 16

Size Distribution of Aerosol Emitted From TF30 Engine
At Normal Rated Power With and Without Ferrocene

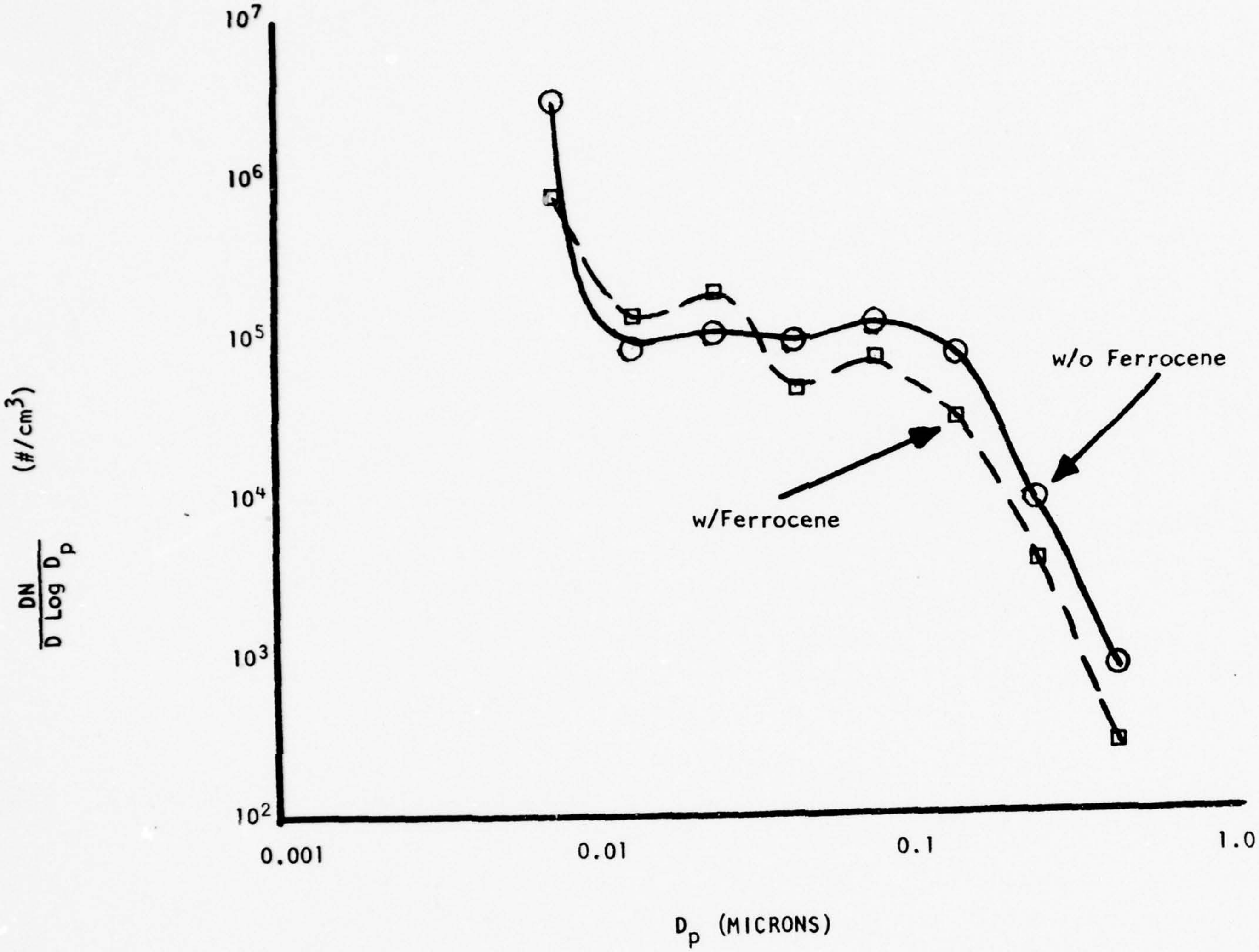


FIGURE 17

Size Distribution of Aerosol Emitted From TF30 Engine
At Military Power With and Without Ferrocene

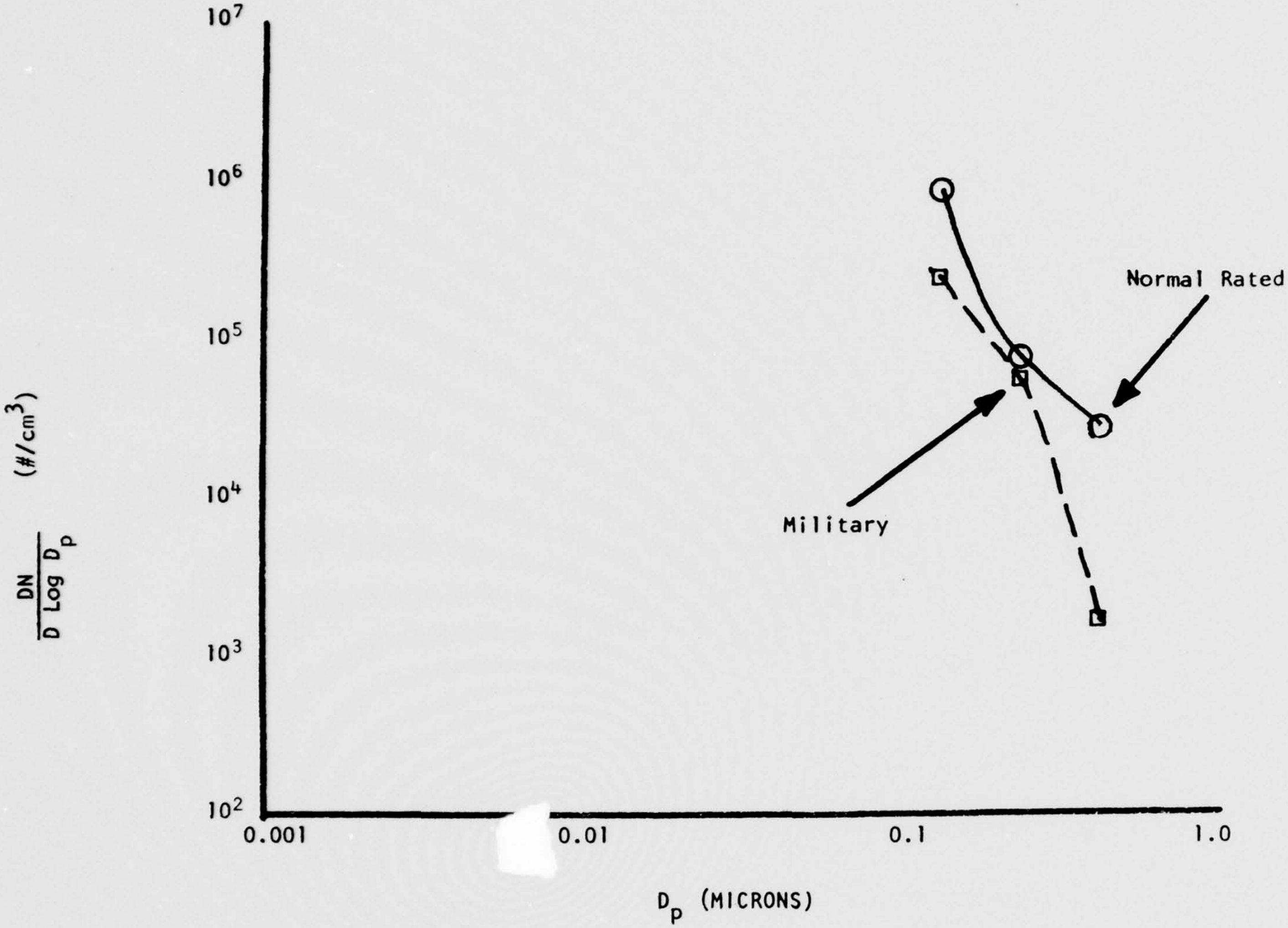


FIGURE 18

Size Distribution of Aerosol Emitted From Test Cell
By TF30 Engine At Normal Rated and Military Power Without Ferrocene

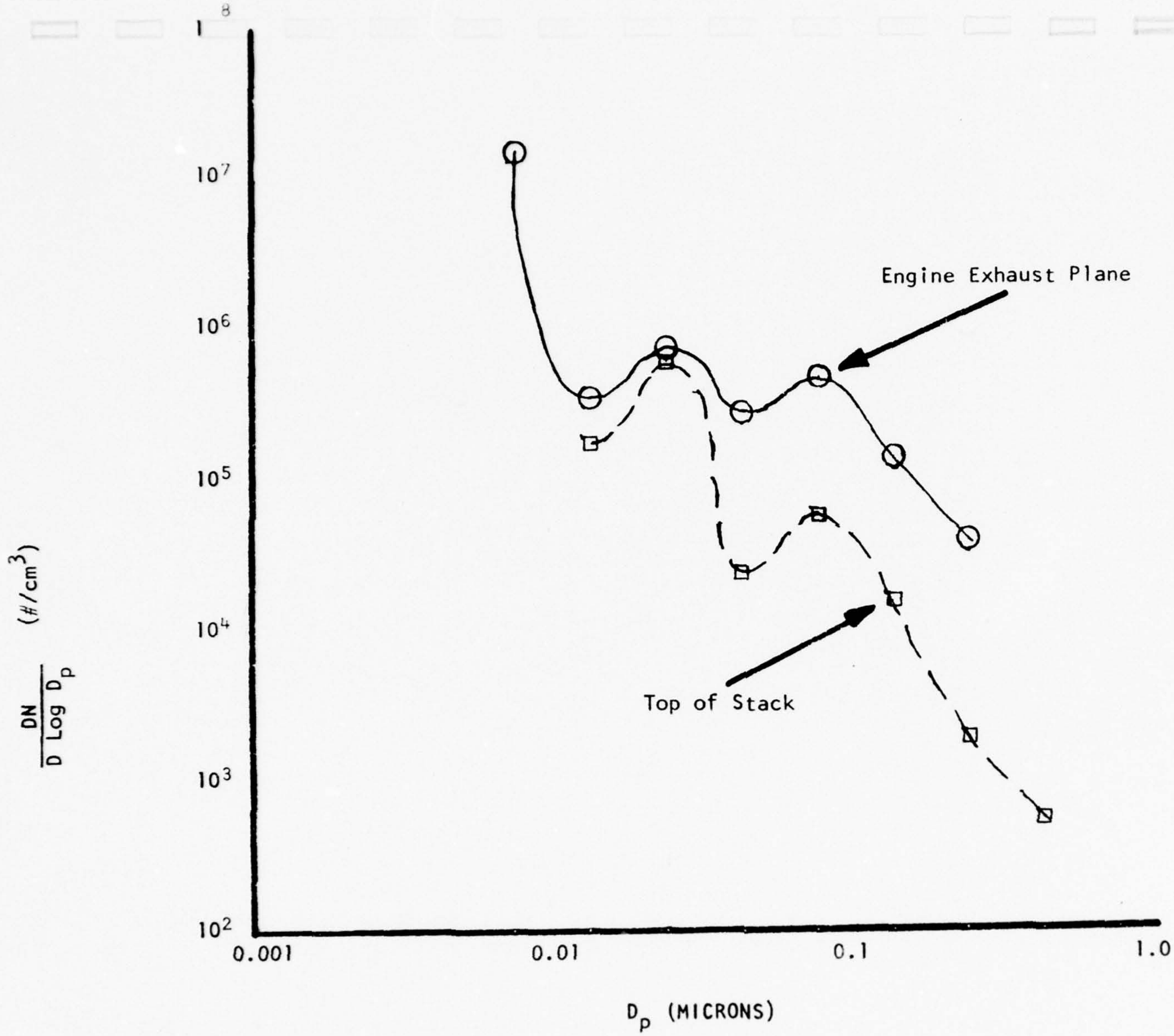


FIGURE 19

Size Distribution of Aerosol Emitted From Tese Cell Stack And TF41 Engine At Idle Power Without Ferrocene

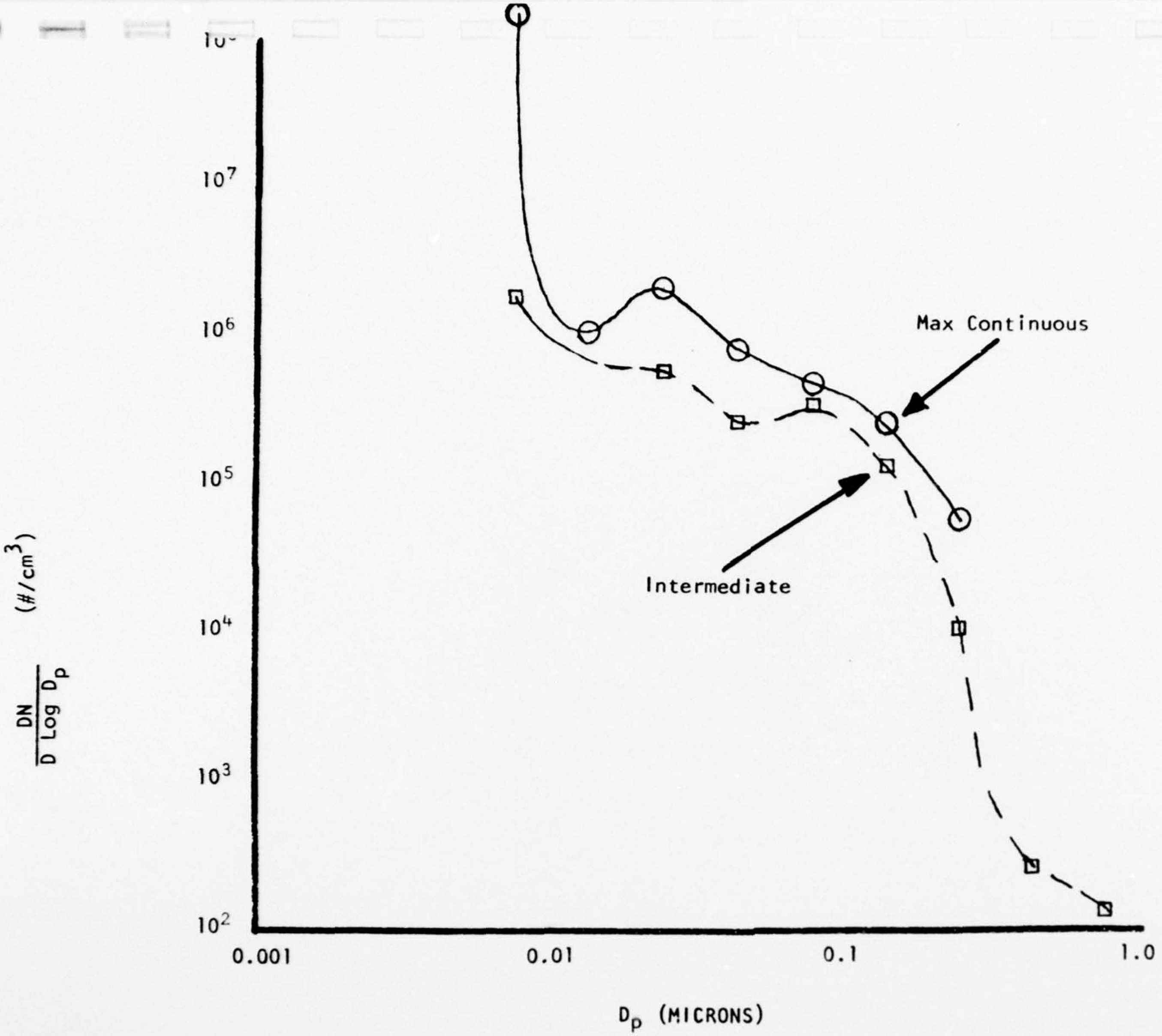


FIGURE 20

Size Distribution of Aerosol Emitted By TF41 Engine
At Normal Rated and Military Power With Ferrocene

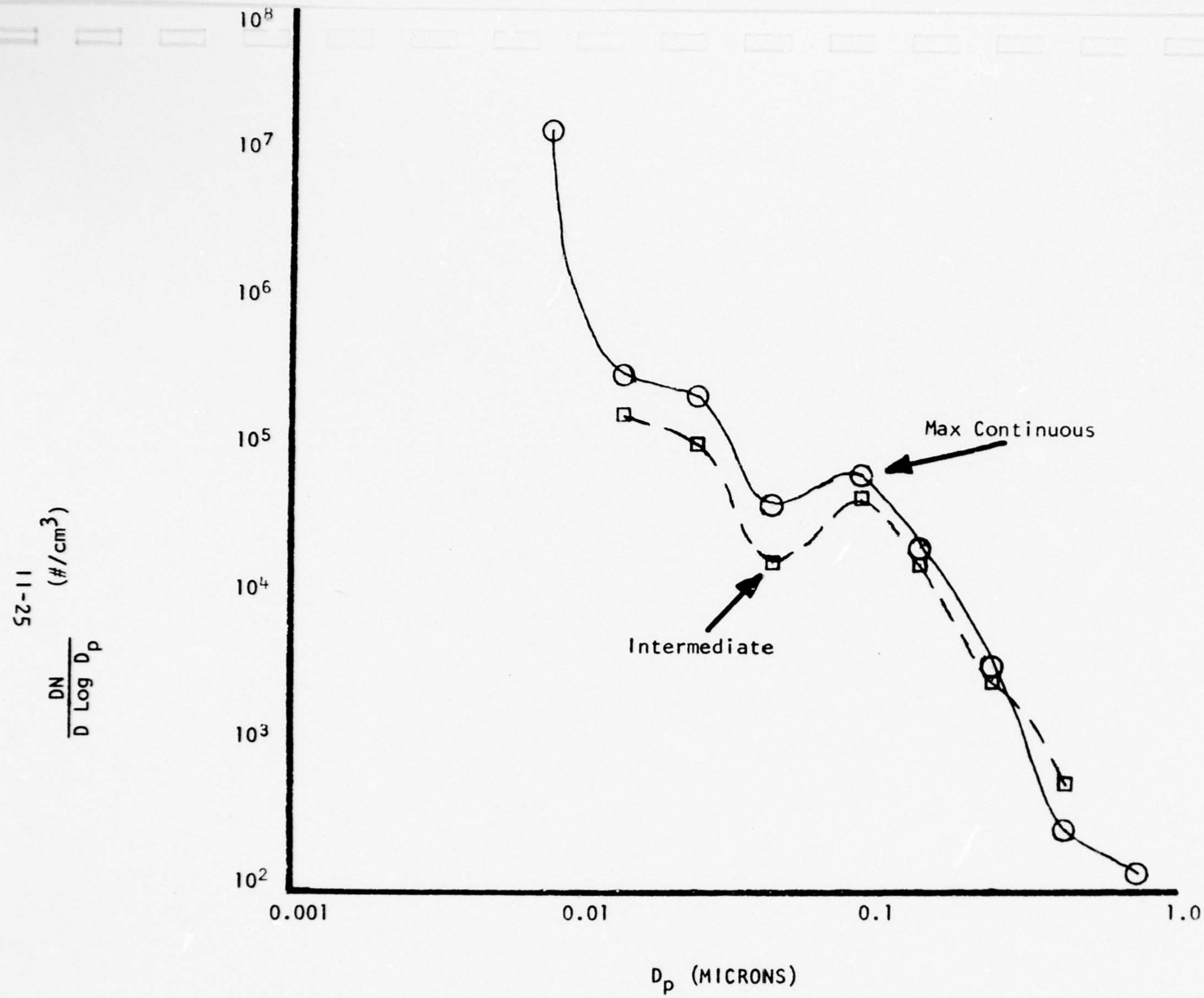


FIGURE 21

Size Distribution of Aerosol Emitted From Test Cell By TF41 Engine
At Normal Rated and Military Power Without Ferrocene

III. CONCLUSIONS

A. Total Mass Emissions

1. Ferrocene reduced particulate emissions from the J52, J57, and TF30 by approximately 50%. The reduction is evident at both the engine exhaust plane and the top of the stack for the J57 and TF30. No engine exhaust plane samples were taken from the J52 due to excess engine nozzle to probe distance.

2. The data for the J79 and TF41 are mixed. Ferrocene reduced emissions from the J79 at 85% RPM and normal rated, but increased them at military power. The TF41 data shows a similar anomaly. More samples from the J79 and TF41 need to be taken to determine the true effect of ferrocene on these engines.

B. Size Distribution

1. Direct comparison of the effect of ferrocene on the aerosol size distribution is possible in Figures 3, 4, 5, 6, 11, 12, 16, and 17. Figures 6, 11, and 16 show a reduction in all aerosol sizes. Figures 4, 5, and 12 show fewer smaller and more larger particles. Figure 17 shows a reduction of the very small and larger sizes. Figure 3 shows an increase in all aerosol sizes.

2. In six of the cases investigated, ferrocene seemed to reduce the number of particles $<0.03\mu$ in diameter. In three of the cases, all particle sizes were reduced. In one case the number of particles actually increased. Unfortunately, it is not possible to compare total mass loadings for this case (Figure 3) due to the loss of one of the samples.

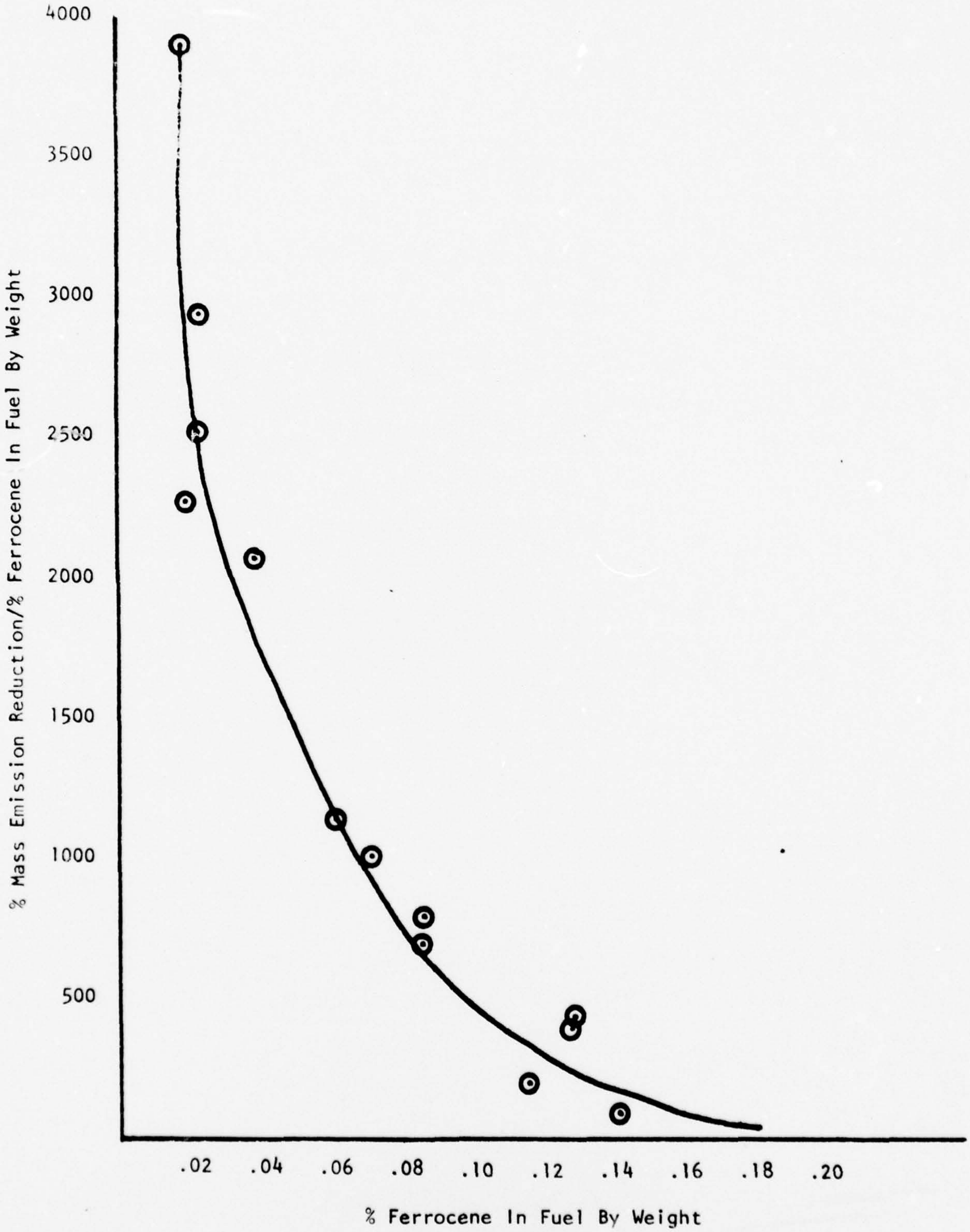
C. Overall Conclusions

1. Ferrocene has been shown to reduce total particulate emissions and visible emissions for three of the gas turbine engines tested. There are indications such reductions will be shown for the remaining two engines (TF41 and J79) with further testing.

2. Figure 22 is a plot of percent mass emissions reduction/percent Ferrocene by weight versus percent Ferrocene by weight for all samples using ferrocene except TF41 and J79 at military. The data points were fitted to an expoential curve using a least squares regression method. The correlation coefficient (r^2) was 0.90.

FIGURE 22

Change in Mass Emissions As A Function of Ferrocene Concentration



APPENDIX B

EFFECTS OF FERROCENE SMOKE ABATEMENT ADDITIVE ON HYDROCARBON EMISSIONS OF TURBINE ENGINES

Effects of Ferrocene
Smoke Abatement Additive on
Hydrocarbon Emissions of
Turbine Engines

Suggs, H. J., Conkle, J. P., Richardson, A.,
Lackey, W. W., and Martin, C. L.

March 1977

USAF School of Aerospace Medicine
Brook AFB TX 78235

Introduction: The primary objective of the USAFSAM/VNL portion of the ferrocene smoke abatement study was to characterize hydrocarbons in the engine exhaust and to determine if the addition of ferrocene significantly changes the hydrocarbons emitted. This knowledge will aid in assessment of any changes in health effect when the additive is used. The hydrocarbon characterization is limited by the technological state-of-the-art to the relatively lighter hydrocarbons, less than about C_{10} - C_{11}.

Background: Our laboratory has been involved for several years in developing methodologies for characterizing hydrocarbons in engine exhaust gases. In the course of this work we did make some measurements of hydrocarbons in a combustor test rig at AFAPL. One of these runs involved ferrocene added to JP5 fuel and the limited data from that run suggested that addition of ferrocene did in fact alter the hydrocarbon composition, possibly to give a more photochemically reactive product. The Alameda ferrocene test program afforded an opportunity to study this alteration in more detail with real engines and with some replication.

Early work has involved sampling with a three stage cryogenic sampler with analysis by GC-MS, but this is not yet a completely proven and validated methodology for engine exhaust sampling. The Alameda ferrocene study afforded opportunity to expand the data base on cryogenic sampling methodology for engine exhaust and at the same time look at another promising and somewhat simpler sampling technique. This is the use of a solid sorbent sampling device, again with GC-MS analysis. Our portion of the study was designed not only to provide basic data on the effect of ferrocene addition on exhaust hydrocarbons, but also to provide additional validation for cryogenic sampling and to evaluate the solid

sorbent sampling methodology. The experiment was also designed to sample both at the engine exit plane and at the test cell exhaust, hopefully to shed some light on the question of whether chemical reactions do occur in the exhaust gas after it leaves the engine tail pipe.

This report will be limited to consideration of the effect of ferrocene addition on exhaust hydrocarbons. Other aspects of the study will be considered in a USAFSAM Tech Report at a later date.

Experimental Design: Since the primary purpose of the study was to look for changes in exhaust hydrocarbons when ferrocene additive is used, sampling was proposed for essentially identical engine operating conditions with and without ferrocene addition. For most engines, the point of maximum smoke formation (and hence maximum ferrocene usage to control smoke) occurs at very near the point of minimum hydrocarbon emission, this point being near rated power. In order to sample with hopefully somewhat higher hydrocarbon emissions but still with close to maximum ferrocene usage, sampling was done at 75% of maximum power. For the TF41 this was 11,150 lb thrust (6900 lb/hr fuel flow) and for the J57 it was 7800 lb thrust (6100 lb/hr fuel flow).

Sample was extracted from the engine exit plane using standard EPA cruciform probes and a heated sample line. A Beckman 402 Flame Ionization Detector (FID) extracted sample continuously from this line to monitor total hydrocarbons (THC). Sample was extracted from the same line to two Tenax solid sorbent sampling trains, one at 0.5 lpm the other at 1 lpm and to the cryogenic sampler at 0.3 lpm. The engine exit plane sampling trains are shown schematically in figure 1 and the equipment is seen in the photographs, figures 2-5.

In the Tenax trains, the cold trap was used to condense and remove excess water before the tubes. The condenser and Tenax tubes operated without heating or cooling and temperatures were 21 ± 2°C during all runs. Tedlar bags were used to collect throughput gas for light hydrocarbon analysis (C_1 to C_3 hydrocarbons are thought to be poorly trapped by Tenax). Since the capacity of the bags is only about 20 liters, flow into the bags was limited to about 0.3 lpm so that gas representative of a 60 minute run could be collected in one bag. Two Tenax tubes in series were used and analyzed separately in order to investigate break through. The two different flow rates were used to investigate the effect of flow rate on break through.

The three stage cryogenic sampler has been described previously (SAM-TR-74-54, Cryogenic Sampling of Turbine Engine Exhaust). A single Tenax tube was used after the cryo trap to determine hydrocarbons not completely removed by the cryo sampler and a Tedlar bag was again used to collect throughput gas to determine C_1 to C_3 hydrocarbons thought to be inefficiently collected in the cryo sampler.

In the course of the first sample run, difficulty with the sampling pumps was experienced. It was found that the pressure in the cruciform probe and sample line was excessive for these pumps. By simply turning the pumps off, the pressure proved adequate to maintain the desired flow rates through all three sampling trains.

At the top of the test cell stack, sample was extracted from a single nozzle probe formed from ¼ inch stainless steel tubing. The nozzle was anchored with a piece of 3 inch angle iron across the southeast corner of the stack.

The sample line led to a Tenax sampling train (only one train, operated at 1 lpm) and to a cryogenic sampling train, both in configuration identical to the trains used to sample from the engine exit plane. The stack sampling trains are shown schematically in figure 6 and the equipment is shown in photographs, figures 7 and 8.

Analysis Procedures: Hydrocarbon analysis of the cryogenic samples is accomplished with a coupled gas chromatograph (Varian Model 1400)--mass spectrometer (Du Pont Model 21-491)--data system (Du Pont 21094). The chromatographic column packing is Porapak Q in a 3-m long by 1.6 mm OD microbore (0.7 mm ID) stainless steel tube. This column, with temperature programming from -100°C to 250°C at approximately 10°C/min, has proven adequate for separation of compounds ranging from methane to C_{10} aliphatic and aromatic hydrocarbons. The chromatographic effluent is split 1/3 to the gas chromatographic flame ionization detector (FID), and 2/3 to the mass spectrometer for sample enrichment via a jet separator and subsequently to the mass spectrometer ionization region. Compound quantitation is accomplished by digital integration (Auto lab IV) of the gas chromatographic FID response. Peak area/ugm is based on a 113 ppm hexane standard "Lot # 020171R" prepared by Matheson Gas Products. Compound identification is accomplished by the MS-data system, based on a data library (approximately 23,900 compounds) comparison of fracture patterns.

Each of the cryosample cylinders is analyzed by heating to 135°C and expanding the gas into an evacuated 3 ml sample loop for injection into the GC-MS. If there is insufficiant material in this 3 ml sample, the sample loop is immersed in liquid nitrogen and the contents of the

cylinder (heated to 135^{o}C) are trapped in the loop for injection into the GC-MS.

Techniques similar to analysis of the cryosets are used for analysis of the sorption tubes (Tenax). The compounds contained within the sorption tube are removed by thermal desorption. The tube is placed into an aluminum heater block at room temperature. Helium gas at 30 cc/min flows through the Tenax tube to the 3 ml sample loop which is immersed in liquid nitrogen. The temperature of the Tenax tube is raised to 240^{o}C in 10 minutes and maintained at this temperature for a total trapping time of 20 minutes. The contents of the 3 ml sample loop are then heated to 115^{o}C and transferred to the GC-MS.

Results: Numerous operational problems plagued the study during set-up and the TF41 engine runs. Four days were required for this phase while the J57 runs were completed within one day with no significant operational problems. The more significant problems encountered by our team included breakage of mounting lugs for the cruciform probes, breakage of the sampling line on the probes, the pump malfunction due to high pressure in the sampling line discussed earlier and a malfunction in a nitrogen regulator. Safety considerations precluded sampling on the stack after sundown. Because of this and the pressure to keep the overall study close to schedule, we were unable to obtain stack samples for the TF41 with ferrocene. Perhaps the most significant and disappointing problem resulted after the study was completed. When the sampling equipment and plastic bag samples arrived back at Brooks AFB it was found that the plastic bag valves had been opened and the bags deflated. It would appear that someone in the shipping department, not

realizing that the contents and not the container was the important thing, deflated the bags to save space. Most of the bags had been measured for THC using the field FID immediately after each run, but this does not give the individual component data we had hoped for. There was sufficient residuel gas in the bags for some study in the lab, but since the valves were open, the data can not be considered valid.

Table I summarizes the data, showing the engine, location, fuel, various sample volumes, total hydrocarbons found inthe various sampling trains, total hydrocarbons found by the field FID both in the engine exit-plane sampling line and in those bags that were checked in the field and the THC and methane concentrations found in the lab analyzed bag residual samples.

It will be noted that, based on the field FID measurements of both the sampling line gas and the plastic bags, the hydrocarbon concentrations after the samplers is greater than that before the samplers. The THC values from the sampling line as measured by the field FID appear to be unusually low for all runs except the TF41 without ferrocene. This may be because the unit is calibrated with a 100 ppmc standard but is measuring concentrations below 10 ppmc.

Cryogenic sampling appears to be significantly more efficient since these results are consistently higher than the Tenax sampling results. Some preliminary lab work tends to confirm this. The inefficiency of the Tenax method appears to be in poor recovery of the adsorbed sample to the GC-MS. The very high cryogenic sample result for the TF41 with ferrocene at the engine exit plane is discounted, for this is the sample collected when the pump malfunctioned.

The fact that THC in the stack gas is little different then in exit-plane gas indicates that ambient air is relatively close to engine exhaust in THC content. Normally the augmentation air would significantly dilute the exhaust giving much lower concentrations at the stack. The composition of the stack gas is significantly different from that of the exit-plane gas. For example, exylene was found consistently in the stack gas, but seen only once in exit-plane gas.

Analysis and interpretation of results is extremely difficult. Most of the difficulty stems from the low concentrations of hydrocarbons and the resultant small mass of sample available for analysis. Discounting the one very high cryogenic sample, only about 1.5 to 43 ug of total hydrocarbons were trapped and removed from the sampling devices. Because of the small amounts of material and the characteristics of the GC-MS and Data System, specific compounds were not identified consistently. Approximately 15% of trapped materials represent compounds either present in very small amounts and/or so poorly resolved by the GC column that identification is impossible. Some specific compounds were identified with a reasonable degree of certainty in one sample but in a similar sample they were not positively identified.

A large number of specific compounds were identified. It is interesting that, considering all engine exit-plane samples and all sampling trains, a total of 47 compounds were identified in the without ferrocene runs while 70 different compounds were identified in the with ferrocene (Tables II & III). This confirms a trend noted in our earlier combustor rig sampling although the significance of this finding is not readily apparent.

Interpretation of the results is somewhat simplified by grouping the compounds identified into chemical classes such as alkanes, alkenes, alcohols, aldehydes ketones, etc. The summary of hydrocarbons found (Table IV & V) reflects these classes. Even with this simplification, interpretation is difficult. Of particular concern are the C_1 to C_3 hydrocarbons. Results for these compounds are very erratic and almost certainly they are inefficiently collected. This makes the loss of the bag samples extremely disappointing. Undoubtedly the alkane, alkene and acetylene results shown in Tables IV & V would be significantly different if we had reliable data on the bag samples.

The most apparent change in hydrocarbon composition of exhaust gas with the addition of ferrocene is the increase in ketones and aldehydes. This increase appears to come at the expense of alkenes and aromatics, although the actual change in alkenes is somewhat obscured by the erratic results and the absence of data on the C_1 - C_3 hydrocarbons not trapped.

Conclusions: The pie charts, figure 9 graphically portray the overall results of the effect of ferrocene addition. No numerical values are assigned for to do so would imply an accuracy that is not warrented by the data. Nevertheless the marked increase in aldehydes and ketones appears real. Even if the C_1 - C_3 hydrocarbons were better defined, the relative change in aldehydes and ketones would probably not be affected. Better definition of the C_1 - C_3 hydrocarbons would probably show whether the increased aldehydes and ketones derived from alkanes or alkenes.

Some preliminary data on recovery efficiency from Tenax tubes suggests an efficiency of around 30%, bringing the tubes into relatively close agreement with the cryosamples. The diminishing fraction collected

in succeeding elements of the sampling trains suggests that sample collection is relatively high (except for C_1 to C_3 alkenes and alkanes) and that the problem probably does rest in the ability to quantitatively remove the compounds of interest to the GC-MS.

As suggested earlier, the field THC measurements appear low in comparison with other Navy measurements made on these engines (approximately 10 ppmc for the TF41 and 8 ppmc for the J57 at the power settings used in this study).

If we assume that in the present samples we are seeing some 30% of the aldehydes and ketones present and that the difference between these THC results and expected THC results consists only of C_1 to C_3 alkanes and alkenes, we can make some very rough estimates of aldehyde and ketone emissions. For 20 minute runs, neglecting time at idle when no ferrocene addition for smoke abatement is required, test runs without ferrocenes would result in emissions of about 0.03 to 0.06 lb of aldehydes and ketones. Similarly, when ferrocene is added the corresponding emissions would be 0.05 to 0.1 lb. This change is not likely to have significant smog formation potential in a given area.

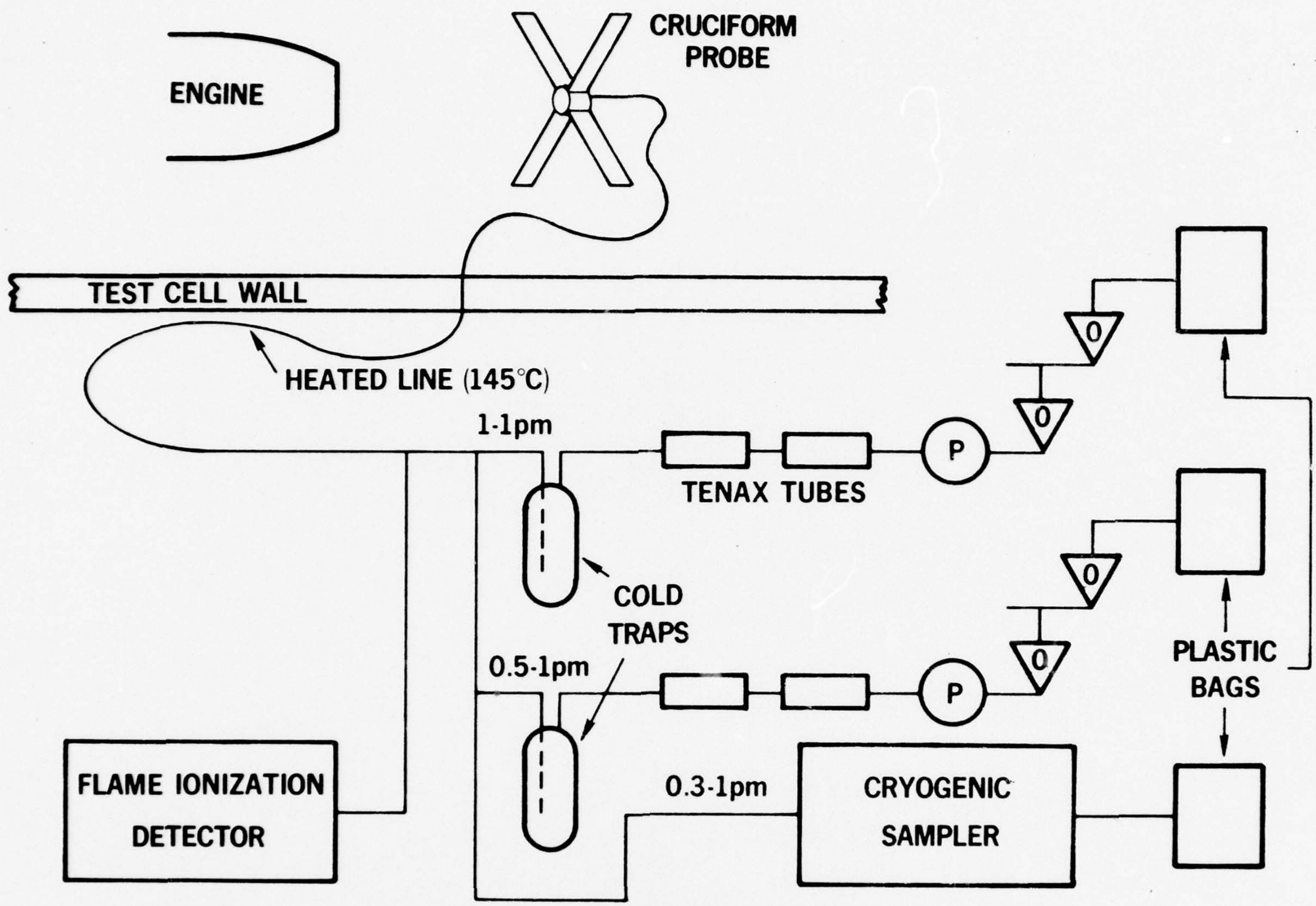


FIGURE 1
SAMPLING TRAIN FOR ENGINE EXIT-PLANE SAMPLING

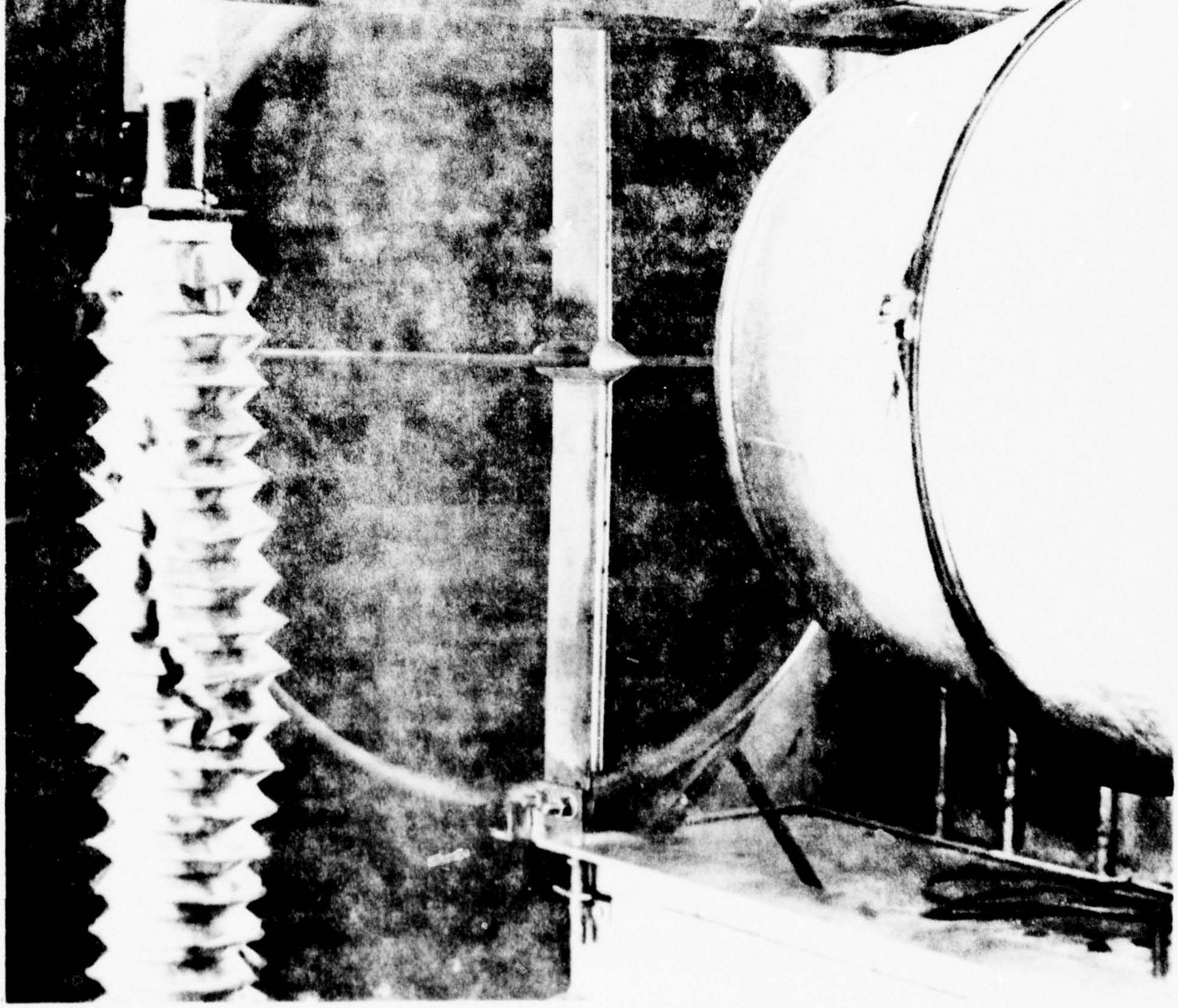


Figure 2. Cruciform Probe/nozzle.

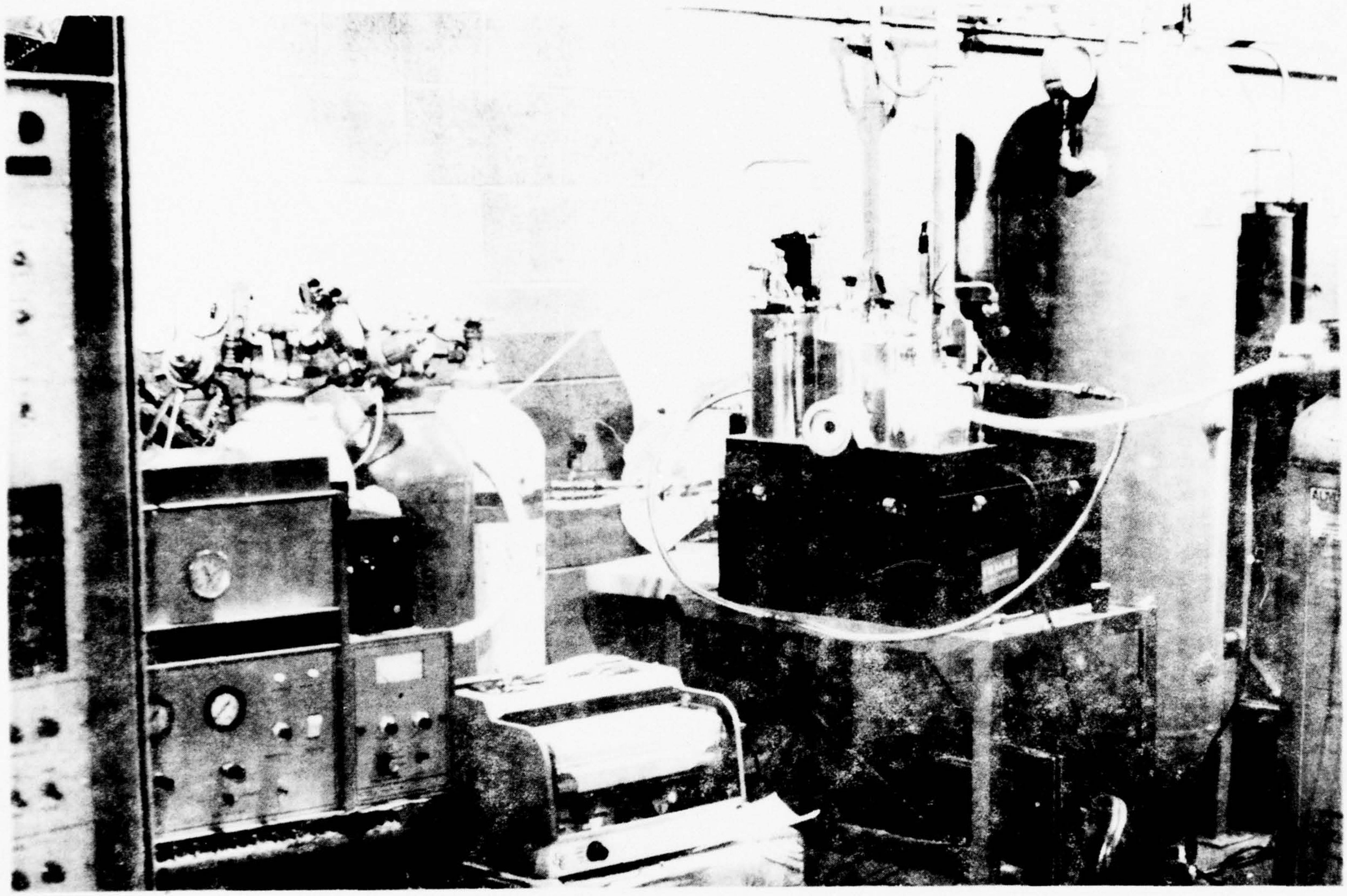


Figure 3. Overall View of Exit-plane Sampling Equipment.

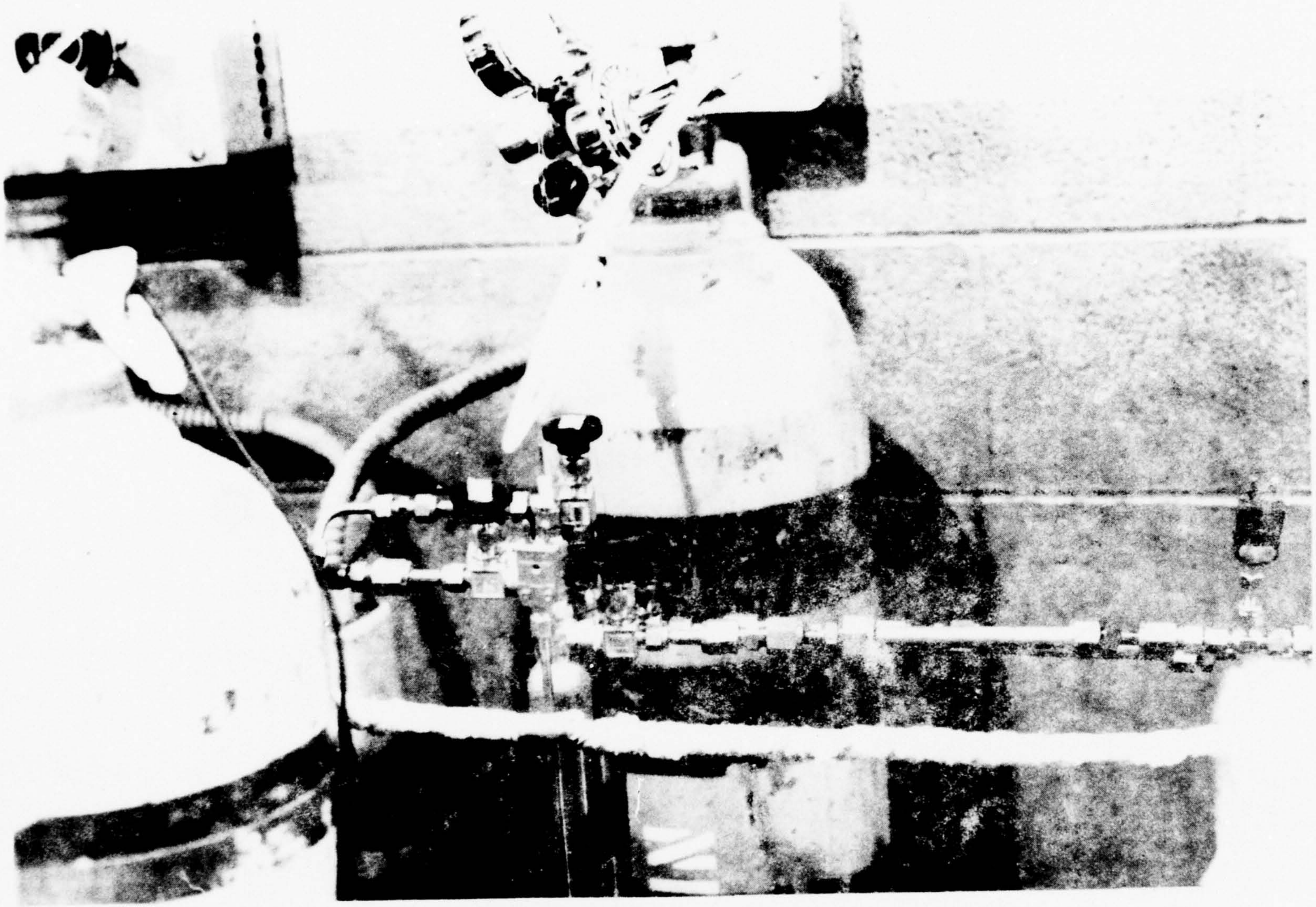


Figure 4. Cold Trap and Tenax Tube Sampling Trains.

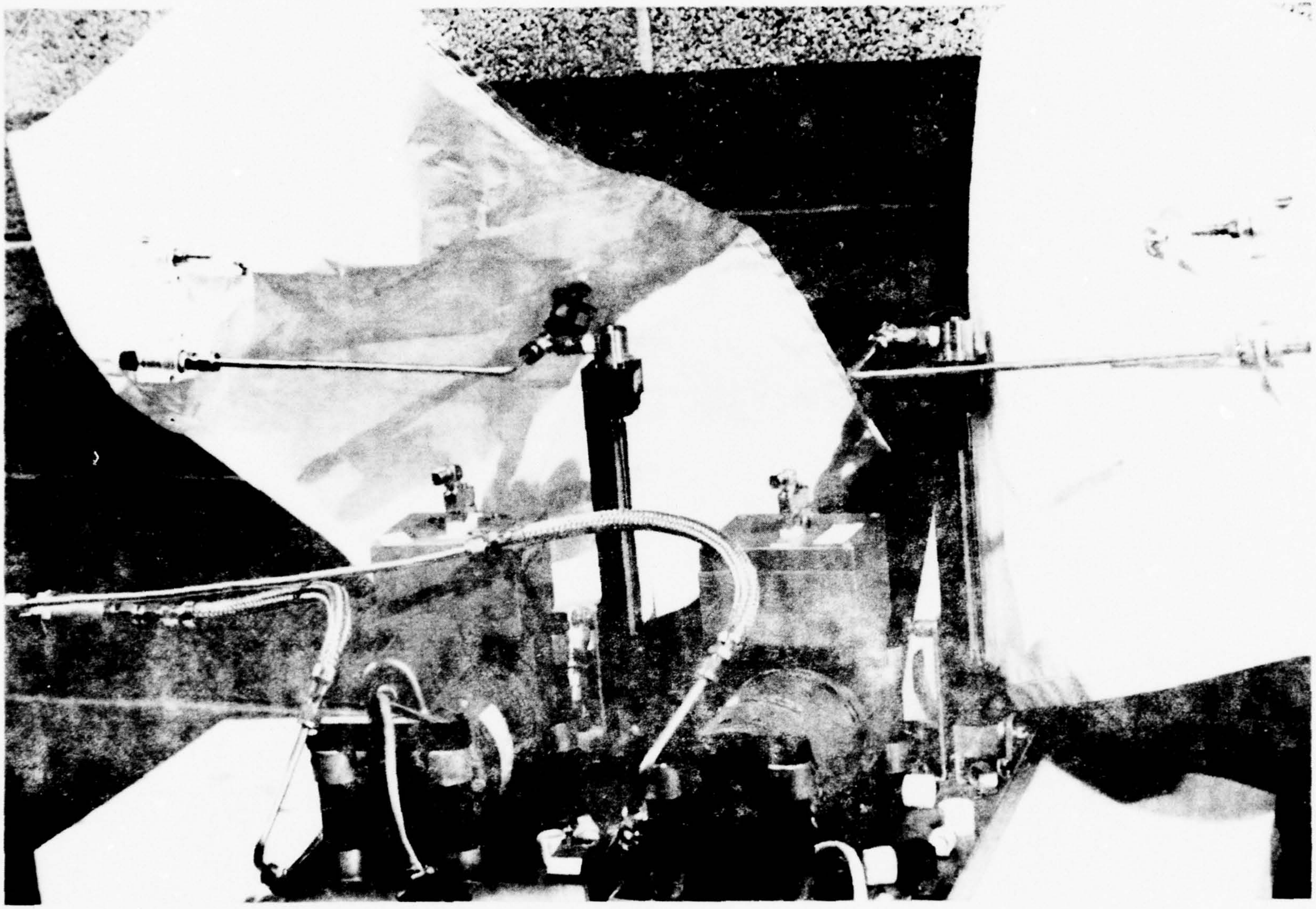


Figure 5. Plastic Bag Sampling After Tenax Train.

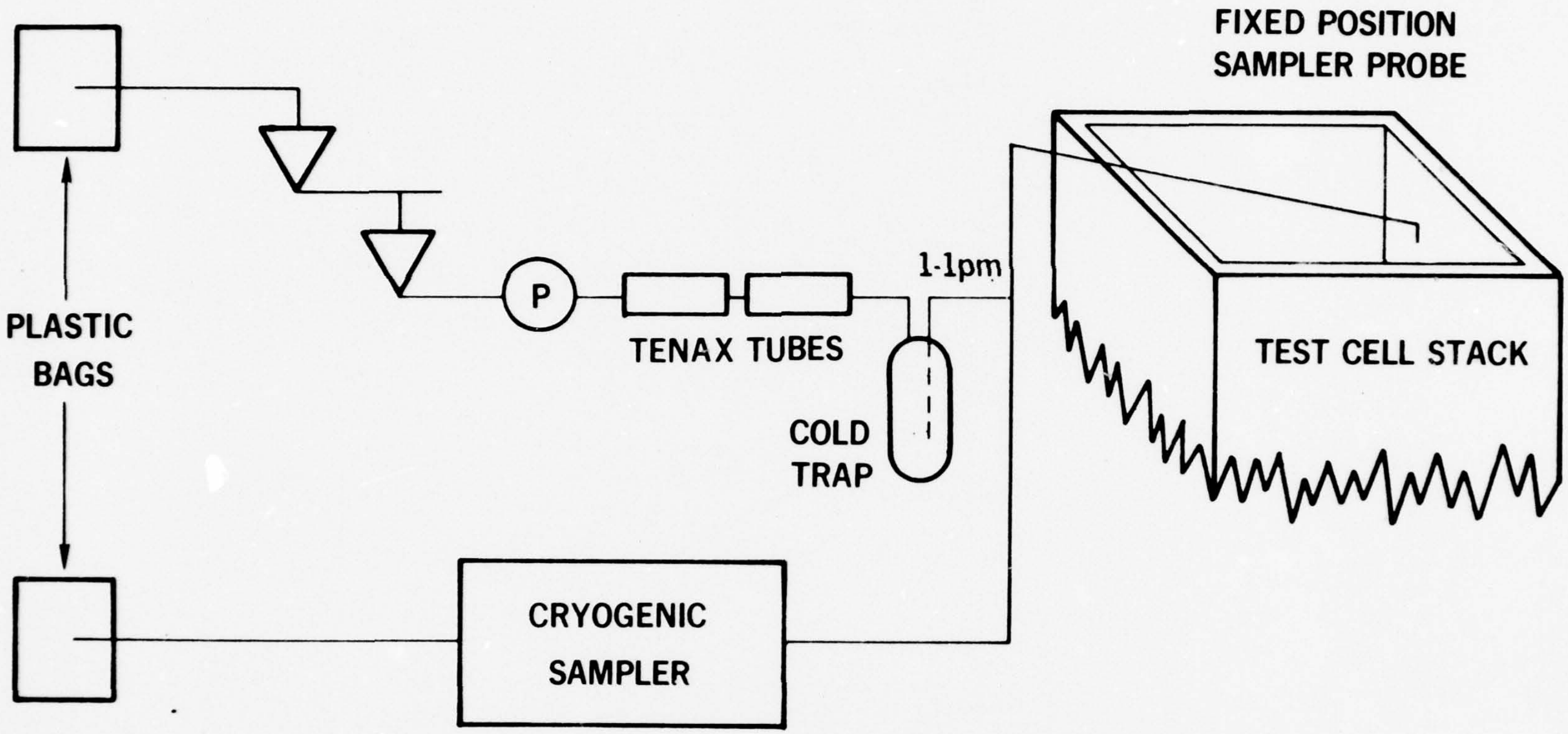


FIGURE 6
SAMPLING TRAIN FOR TEST CELL STACK SAMPLING

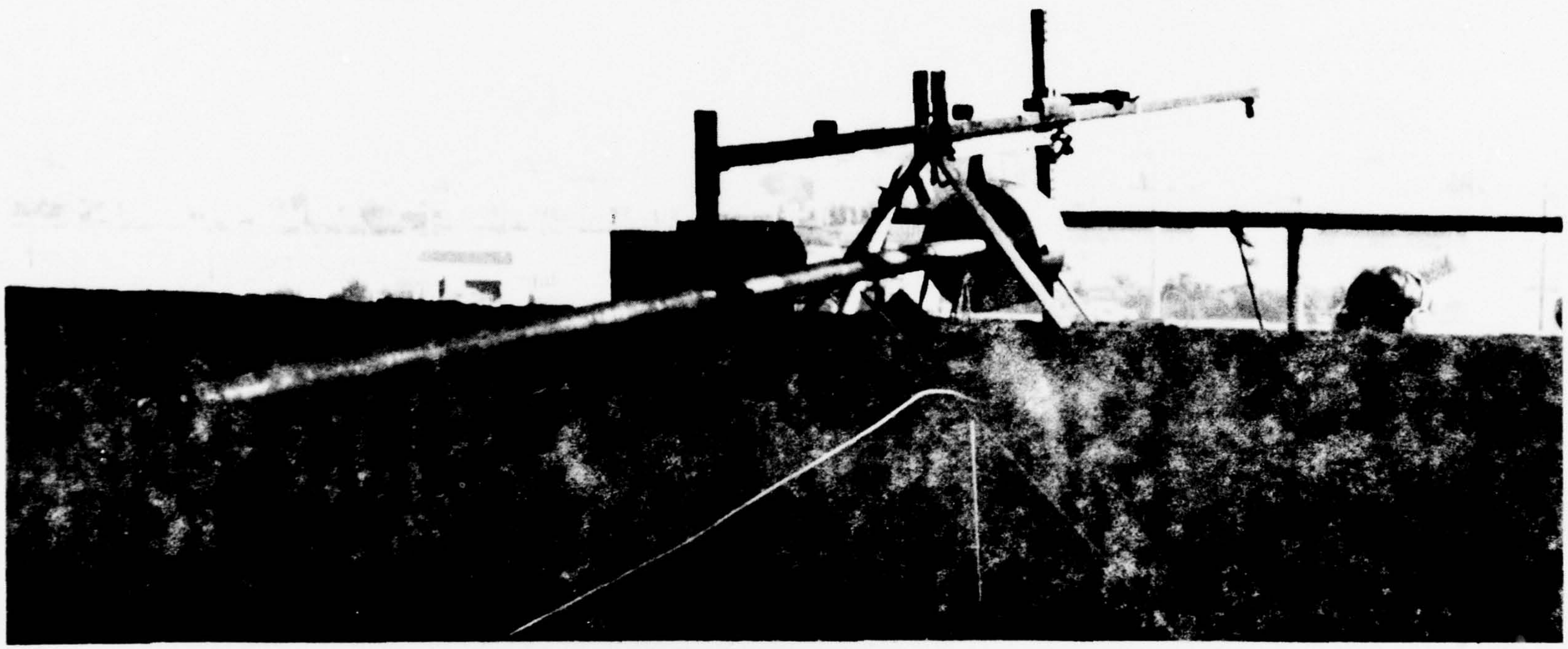


Figure 7. Fixed Stack Sampling Probe and Line.

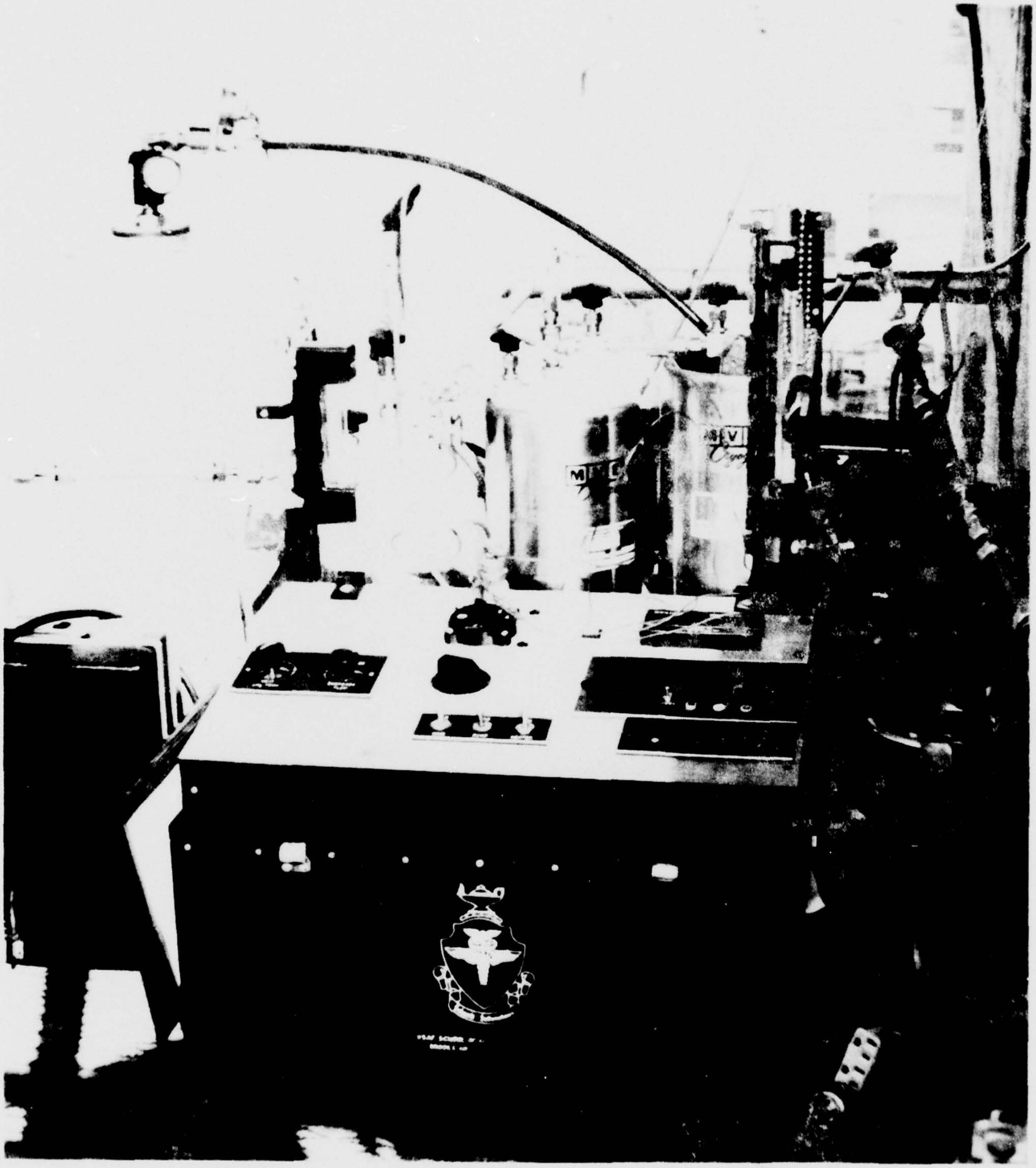


Figure 8. Sampling Equipment Used at Stack.

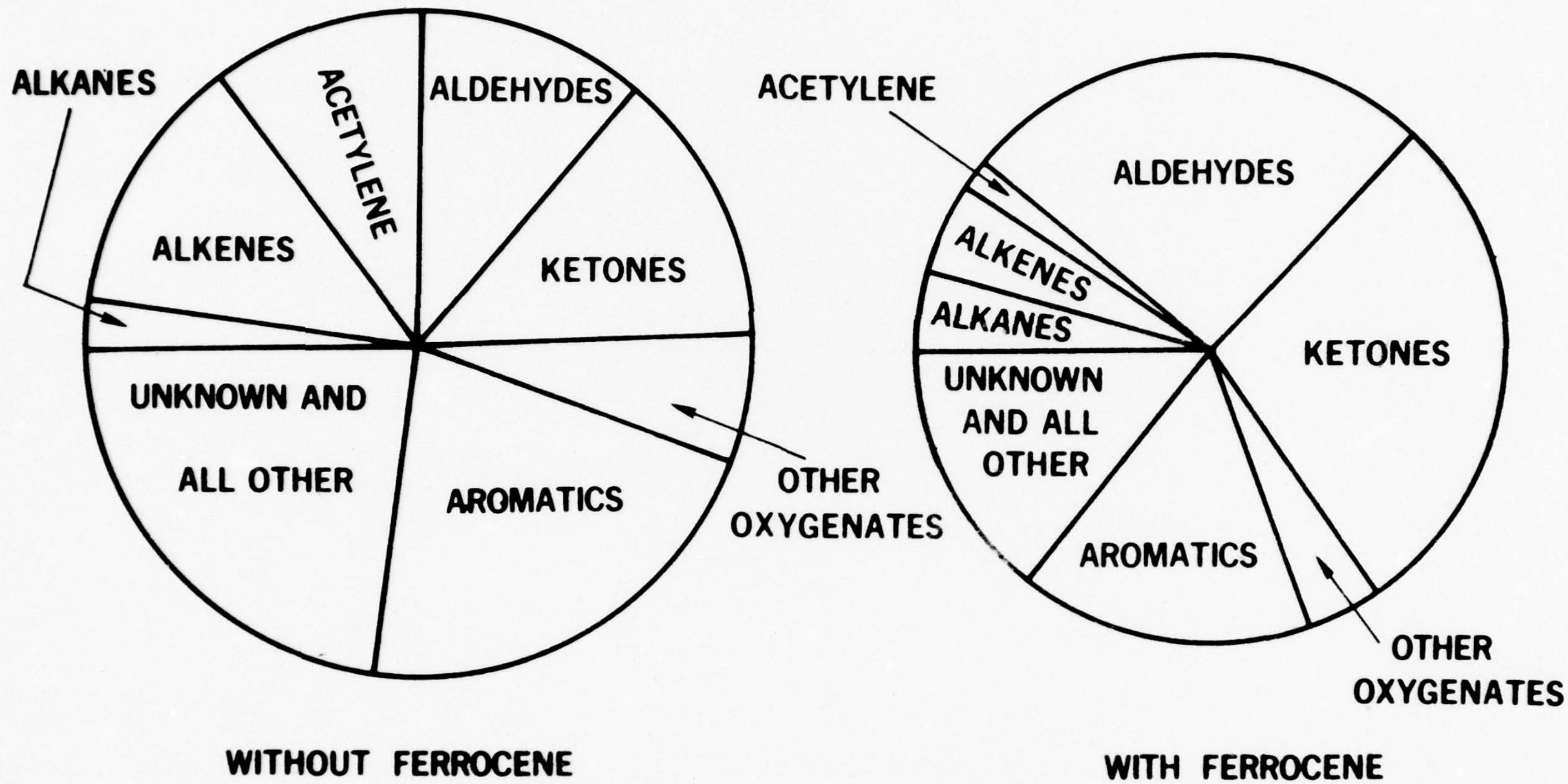


FIGURE 9
EFFECT OF FERROCENE ON EXHAUST GAS HYDROCARBONS

Table I. Sampling Data and Results

Location	Engine	Ferrocene Added	Total HC-Field FID	Sample Train	Sample Volume liters	Sample Train Analysis		Gas Bag Analysis (ppm-c)		
						$\mu g/m^3$ (as hexane)	ppm-c	Field FID	Lab FID	Lab Methane
Engine Exit Plane	TF 41	yes	2.0 ppmc	Tenax 1/2 lpm	22.19	120	0.20	2.4	9.7	1.4
			over	Tenax 1 lpm	42.4	154	0.26	1.4	8.2	0.8
			60 min	Cryo	26.4	7100	12.1	3.2	11.2	1.1
		no	8.8 ppmc	Tenax 1/2 lpm	10.0	155	0.26	NS	18.8	1.1
			over	Tenax 1 lpm	20.0	164	0.28	NS	NS	NS
			16 min	Cryo	6.6	767	1.31	NS	5.8	1.9
	J57P10	yes	2.5 ppmc	Tenax 1/2 lpm	30.0	81	.14	2.2	7.2	0.8
			over	Tenax 1 lpm	60.0	72	.12	2.7	8.2	1.3
			35 min	Cryo	18.0	274	.47	3.0	12.3	2.0
		no	1.9 ppmc	Tenax 1/2 lpm	31.75	108	.18	3.4	8.7	2.1
			over	Tenax 1 lpm	63.0	49	.08	4.4	9.4	1.3
			60 min	Cryo	18.63	185	.32	5.6	7.6	3.0
Cell Stack	TF 41	no	-	Tenax	68.0	136	.23	NS	8.2	0.4
				Cryo	19.8	2040	3.47	NS	8.2	0.4
	J57P10	yes	-	Tenax	60.0	125	.21	4.4	10.9	1.0
				Cryo	18.9	1000	1.70	4.7	7.2	0.7
		no	-	Tenax	60.0	134	.23	5.9	8.2	0.6
				Cryo	18.0	1350	2.30	3.1	9.4	1.2

TABLE II. Hydrocarbons Identified
Without Ferrocene Additive

Alkanes	**Alcohols**
*Methane	*Methanol
*Ethane	*Ethanol
*Propane	Propanol
*Butane	Methylbutanol
Methyl propane	Heptanol
*Pentane	**Aldehydes**
Dimethyl butane	*Ethanal
*Methyl hexane	*Propanal
Cyclo Alkanes	*Butanal
Isopropyl cylopropane	Pentanal
*Cyclohexane	Hexanal
Ethyl cyclopentane	Methyl pentanal
Alkenes	**Arometic**
*Ethene	*Benzene
*Propene	*Toluene
*Butene	**Ketones**
*Methyl propene	*Propanone
Pentene	*2-Butanone
*Hexene	**Unsaturated Ketones**
Heptene	Methyl vinyl Ketone
Acetylenes	**Diones**
*Acetylene	2,3-Pentane dione
Unsaturated Aldehydes	
Methyl propenal	

Unsaturated Diols

Butene-1, 4-diol

Other Oxygenated

Furan
*Ethyl vinyl ether
Epoxy butane

Halogenated Cpds

*Chloromethane
Chlorooctane

Nitrogen Cpds

*Nitromethane
*Trinitroethane

Sulfur

2-Methyl-1-pentanethiol

Other

*6,6-dimethylfulvene

* - Denotes compounds found both with and without ferrocene.

TABLE III. Hydrocarbons Identified With Ferrocene Additive

Alkanes	Alkenes
*Methane	*Ethene
*Ethane	*Propene
*Propane	*Butene
*Butane	*Methyl propene
*Pentane	*Hexene
Methyl butane	Methyl hexene
Hexane	Dimethyl pentene
Methyl pentane	Octene
Heptane	
*Methyl hexane	**Cyclo Alkenes**
Octane	
Methyl heptane	Cyclobutene
Dimethyl hexane	
Trimethyl pentane	**Acetylenes**
Nonane	
Methyl octane	*Acetylene
Dimethyl heptane	
Methyl ethyl hexane	**Alcohols**
Tetramethyl pentane	
Dimethyl octane	*Methanol
Propyl heptane	*Ethanol
	Methyl propanol
Cyclo Alkanes	
	Aldehydes
Methyl cyclopentane	
*Cyclohexane	*Ethanal
Methyl cyclohexane	*Propanal
Isopropyl cyclopentane	*Butanal
	Aromatic
	*Benzene
	*Toluene
	2,2-Dimethyl-1-phenyl propane
	Xylene

Ethers

Methyl allyl ether
*Ethyl vinyl ether
Methyl vinyl ether
Isobutyl vinyl ether

Ketones

*Propanone
*2-butanone
2-pentanone
Methyl pentanone
2-hexanone

Unsaturated Aldehyds

Propenal (acrolein)

Other Oxygenated Cpds

Isobutyl oxide
2,3-Epoxy butane
2,5-dihydro furan
BB-dimethyl propiolactone
Methyl allyl acetate

Halogented Cpds

*Chloromethane
Fluorobutane
Chloropentane
Trichloroethylene
R-113
1,1,2,2-tetrachloro-1,2-difluoro ethane

Nitrogen Cpds

*Nitromethane
*Trinitroethane

Others

Trimethyl-1-fluorosilane
*6-6,Dimethyl fulvene
Carbon disulfide

* - Denotes compounds found both with and without ferrocene.

Table IV. Summary of Hydrocarbons Found - TF41A2A (μg/m3 as hexane)

	WITH FERROCENE			WITHOUT FERROCENE				
	ENGINE			ENGINE			STACK	
	Tenax 1/2 lpm	Tenax 1 lpm	Cryo System	Tenax 1/2 lpm	Tenax 1 lpm	Cryo System	Tenax 1 lpm	Cryo System
Alkanes	6.25	18.3	194	3.35	2.52	122	0.99	176
Cyclo Alkanes	0.23	2.10	163			2.43	5.65	120
Alkenes	5.01	4.51	756	18.6	19.8	155	25.6	46.2
Cyclo Alkenes	2.05	2.96						
Dienes								16.4
Acetylenes	1.56	0.64	0.43	3.28	48.0	95.4	0.18	0.57
Alcohols	0.44	3.39	26.1	0.37	1.30	19.3	1.81	103
Unsaturated Alcohols							0.08	
Unsaturated Diols						0.92	0.14	
Aldehydes	30.0	25.4	16.6	22.0	25.2	69.6	4.03	274
Unsaturated Aldehydes							4.62	
Ketones	35.6	23.6	1290	28.0	14.6	54.0	6.00	501
Cyclo Ketones								17.2
Aromatics	14.7	17.2	1600	38.0	31.9	101	56.4	259
Halogenated Compounds	0.66	0.31	714		2.26	13.2	2.25	0.36
Nitrogen Compounds	2.46	0.34	191	9.73	7.47	5.39	1.10	14.2
Esters								26.0
Ethers	2.80	0.96	2.45				3.23	
Epoxy Compounds							0.30	
Sulfur Compounds		0.04				0.84	0.56	
All Others	0.67	11.4	191			25.8	3.18	82.9
Unknowns	18.2	26.8	1950	32.0	11.1	99.2	19.6	401
TOTAL	120	154	7190	155	164	767	136	2030

Table V. Summary of Hydrocarbons Found - J57P10 (μg/m3 as hexane)

	WITH FERROCENE					WITHOUT FERROCENE				
	ENGINE			STACK		ENGINE			STACK	
	Tenax 1/2 lpm	Tenax 1 lpm	Cryo System	Tenax 1 lpm	Cryo System	Tenax 1/2 lpm	Tenax 1 lpm	Cryo System	Tenax 1 lpm	Cryo System
Alkanes	0.84	2.23	15.4	8.96	143	2.10	2.14	0.54	20.0	199
Cyclo Alkanes		0.34	1.93	4.64	17.8	0.72		0.68	7.51	18.0
Alkenes	3.69	1.88	2.47	12.1	38.9	14.7	0.91	1.29	27.3	11.9
Cyclo Alkenes										
Dienes				0.02	8.69				0.36	
Acetylenes	1.11	1.34	0.47	10.5	0.56	23.9	0.24	0.39	18.7	0.38
Alcohols	2.26	0.52	8.30	2.66	37.3	8.09		2.33	1.74	50.2
Unsaturated Alcohols										
Unsaturated Diols										
Aldehydes	19.6	14.0	72.5	4.46	198	7.43	3.42	61.0	6.63	369
Unsaturated Aldehydes	3.24	2.01		3.43					8.00	
Ketones	22.3	15.6	17.8	6.97	148	7.10	6.28	34.1	12.0	180
Cyclo Ketones										
Aromatics	17.8	22.9	39.3	41.1	184	21.0	20.2	21.9	41.2	187
Halogenated Compounds	0.43		3.28	1.28	23.6	0.01		0.02	3.10	5.37
Nitrogen Compounds	1.72	0.35	13.4	1.26	1.75	2.15	2.12	14.7	0.2	57.6
Esters	0.24	0.67							3.72	
Ethers				2.30		2.25				20.2
Epoxy Compounds	1.26						3.20			
Sulfur Compounds				2.89		1.25				
All Others			4.59		6.66	5.02				43.3
Unknowns	6.44	10.5	19.3	24.1	148	15.2	10.7	41.8	7.29	179
TOTAL	81.2	72.3	274	125	1000	107	49.1	185	134	1351

APPENDIX C

TOTAL HYDROCARBON EMISSIONS FROM J57 AND TF41 ENGINES DURING FERROCENE-CONTAINING FUEL EVALUATIONS

REPORT NO. AESO 111-77-1
FEBRUARY 1977

TOTAL HYDROCARBON EMISSIONS FROM J57 AND TF41 ENGINES DURING FERROCENE-CONTAINING FUEL EVALUATIONS

NAVAL ENVIRONMENTAL PROTECTION SUPPORT SYSTEM
NAVAL AIR SYSTEMS COMMAND
AIRCRAFT ENVIRONMENTAL SUPPORT OFFICE
NAVAL AIR REWORK FACILITY
NORTH ISLAND, CALIFORNIA 92135

ABSTRACT

The total hydrocarbon content of the exhaust gas from a J57 and a TF41 engine was measured as part of testing to determine the effect of ferrocene-containing fuel on the operation of the engine. Measurements were made at the exhaust plane of the engine. Most hydrocarbon concentrations were in the range of 2-4 ppmC.

TABLE OF CONTENTS

LIST OF TABLES

I. INTRODUCTION

Special tests to determine the effect of ferrocene-containing fuel on the operational characteristics and the components of gas turbine engines were initiated at the Naval Air Rework Facility (NAVAIREWORKFAC), North Island on 8 November 1976 and at NAVAIREWORKFAC, Alameda on 29 November 1976. These tests were coordinated by Naval Air Propulsion Test Center (NAVAIRPROPTESTCEN). The main purpose of these tests was to evaluate the engine after 10-hour operation using ferrocene-containing fuel. In related testing, the Aircraft Environmental Support Office (AESO) measured gaseous, smoke and particulate emissions at NAVAIREWORKFAC, North Island and total hydrocarbon and particulate emissions at NAVAIREWORKFAC, Alameda. The United States Air Force School of Aerospace Medicine (USAFSAM) collected hydrocarbon samples at NAVAIREWORKFAC, Alameda.

This report gives the results of the total hydrocarbon measurement by AESO at NAVAIREWORKFAC, Alameda.

II. EXPERIMENTAL

A. EQUIPMENT

1. Hydrocarbon Analyzer

A Beckman Model 402 Hydrocarbon Analyzer was used for the determination of total hydrocarbons. The zero reference was "zero" air. The span calibration gas was 50.8 ppm propane referenced to National Bureau of Standards "Standard Reference Material 1667" (Propane in Air, 46.3 $\pm$ 0.5 ppm by volume.)

2. Sampling Probes

Twelve-hole-cruciform probes were used to collect gaseous emission samples at the exhaust plane of the engine. Each arm of the probe contained three holes of the sizes and at the locations specified in Table II-1

TABLE II-1

Sizes and Locations of Holes in Cruciform Probes

Engine	Hole diameter inches	Location of holes from the center of the probe inches		
J57	1/4	4 7/8	8	10 1/4
TF41	1/8	5 1/4	9	11 1/2

Samples from all twelve holes were combined into a single stream before being put in the sample line.

3. Sample Line

The sample line between the probe and the instruments was a 50-foot-insulated-Teflon-core line (3/8" O.D.) maintained at

$300 \pm 10^{\circ}F$. The sample line was pressure tested both before and after use to verify that there were no leaks during the sampling. The sample line was divided at the instrument end. One branch went to the AESO hydrocarbon analyzer and the other to the USAFSAM three-stage cryogenic sampler.

b. When an engine was in operation, the pressure in the sample line was higher than could be regulated to operational range by the flow control system of the hydrocarbon analyzer. The pressure was adjusted to the operational range of the instrument by adding an adjustable flow-restricting valve between the sample line and the hydrocarbon analyzer.

B. COLLECTION AND ANALYSIS OF DATA

1. Total Hydrocarbon Analysis of Exhaust Gas Stream

AESO made continuous measurements of the total hydrocarbon content of the gas stream at the engine exhaust plane during the collection of cryogenic samples by USAFSAM. Each sample was collected for about one hour. Except for one run in which the probe broke, cryogenic samples were collected at the exhaust plane for both the TF41 and the J57 engines each operating with either regular JP-5 fuel or JP-5 fuel containing ferrocene. Cyrogenic samples of the exhaust stream at the top of the stack were collected during some of these runs. The continuous recorder traces from the AESO hydrocarbon analyzer output show every little deviation throughout the sampling periods. Zero and span references were recorded at arbitrary intervals. Tables II-2 through II-5 report representative total hydrocarbon values. For best accuracy, each reported reading was made either just before or just after the recording of the zero and span references.

TABLE II-2

Hydrocarbon Emissions from TF41-A-2A engine, JP-5 Fuel Containing Ferrocene

Engine	TF41-A-2A
Serial number	141479
Fuel	JP-5 Containing ferrocene
Power setting	75% Thrust
Test cell	Alameda 15
Probe	TF41
Date	1 December 1976

Sample	Elapsed time Minutes	Total hydrocarbons ppmC
1	7	3.5
2	12	2.3
3	41	1.9
4	46	1.9
5	62	2.1
6	72	1.9

TABLE II-3

Hydrocarbon Emissions from a TF41-A-2A Engine, JP-5 Fuel

Engine	TF41-A-2A
Serial number	141479
Fuel	JP-5, no ferrocene
Power setting	75% Thrust
Test cell	Alameda 15
Probe	J57[a]
Date	2 December 1976

Sample	Elapsed time Minutes	Total hydrocarbons ppmC
1	16[b]	8.8

a. The J57 probe was used in this run because the TF41 probe broke during a prior endurance test.

b. The total time of the sample collection at the exhaust plane was limited to about 20 minutes. The probe broke during this run. A repetition of this run could not be scheduled.

TABLE II-4

Hydrocarbon Emissions From A J57-P-10 Engine, JP-5 Fuel

Engine	J57-P-10
Serial number	627207
Fuel	JP-5, no ferrocene
Power setting	75% Thrust
Test cell	Alameda 15
Probe	J57
Date	3 December 1976

Sample	Elapsed time Minutes	Total hydrocarbons ppmC
1	2	4.4
2	17	2.6
3	32	2.6
4	50	2.2

AD-A047 659 NAVAL AIR PROPULSION TEST CENTER TRENTON N J PROPULS--ETC F/G 21/4
EVALUATION OF THE EXTENDED USE OF FERROCENE FOR TEST CELL SMOKE--ETC(U)
OCT 77 A F KLARMAN
UNCLASSIFIED NAPTC-PE-110 NL

2 OF 2
AD
A047659

END
DATE
FILMED
1- 78
DDC

TABLE II-5

Hydrocarbon Emissions from a J57-P-10 Engine, JP-5 Fuel Containing Ferrocene

Engine	J57-P-10
Serial number	627207
Fuel	JP-5 containing ferrocene
Power setting	75% Thrust
Test cell	Alameda 15
Probe	J57
Data	3 December 1976

Sample	Elapsed time Minutes	Total hydrocarbons ppmC
1	2	1.6
2	15	2.8
3	45	1.8
4	60	1.5

2. <u>Analysis Of Bag Samples</u>.

USAFSAM collected bag samples from the exhaust stream before and after it passed through the three stage cryogenic sampler. The sample collected before the cryogenic sampler passed through a water trap and a Tenax trap before entering the sample bag. Tenax is an adsorbent marketed by Applied Science Labs., State College, PA. This sample is referred to as the "Tenax" bag sample. The sample collected after the cryogenic sampler passed through a Tenax trap and then into the sample bag. This sample is referred to as the "Cryogenic" bag sample. Each bag sample was collected for about one hour. Bag samples from measurements at the exhaust plane of the engine were analyzed by AESO for total hydrocarbon content immediately after each run. Bag samples from the top-of-the-stack sampling position were analyzed at the conclusion of the J57 run with ferrocene-containing fuel.

The total hydrocarbon concentration for each bag is reported in Table II-6. AESO measurements were made on each bag by drawing a sample through the hydrocarbon analyzer for about 20 seconds.

3. <u>Related Measurements</u>

At arbitrary times during the testing, AESO measured the total hydrocarbon content of the ambient air in the test cell and in the service room betweem cells 15 and 16 in which the AESO and USAFSAM instruments were located. Measurements on test cell air were made when the engine was not in operation. Total hydrocarbon concentration in the test cell ranged from 5.9 to 11.8 ppmC and in the service room, usually from 5.2 to 9.6 ppmC. On one occasion, due to leakage in the ferrocene injection system the total hydrocarbon concentration in the service room reached 40 ppmC.

TABLE II-6

Total Hydrocarbons Content of Bag Samples

Engine	Ferrocene in fuel	Probe location	Bag number	Bag sampling location	Flow rate l/min	Total hydrocarbons ppmC
TF41-A-2A	yes	Engine	1	a	a	2.4
	yes	exhaust	2	a	a	1.4
	yes	plane	3	a	a	3.2
J57-P-10	no	Engine	1	Tenax	1.0	2.7
	no	exhaust	2	"	0.5	2.2
		plane	3	Cryogenic	-	3.0
J57-P-10	yes	Engine	1	Tenax	1.0	4.4
	yes	exhaust	2	"	0.5	3.4
	yes	plane	3	Cryogenic	-	5.6
J57-P-10	no	Top of	1	Cryogenic	-	4.7
	no	stack	2	Tenax	1.0	4.9
J57-P-10	yes	Top of	3	Tenax	1.0	5.9
	yes	stack	4	Cyrogenic	-	3.1

[a] Not known

III. CONCLUSION

For a J57-P-10 and a TF41-A-2A engine operating at 75 percent thrust and using either JP-5 fuel or JP-5 fuel containing ferrocene, the total hydrocarbon concentration of the gas stream at the exhaust nozzle of the engine usually was in the range of 2-4 ppmC.

APPENDIX D

FERROCENE TEST FOR TEST CELL SMOKE ABATEMENT; EVALUATION OF J79-GE-8D, TF41-A-2A, J57-P-10, J52-P-6B AND TF30-P-6C ENGINE PERFORMANCE AND HOT SECTION INSPECTIONS

OPNAV 5216/144(REV 6-70)
S/N 0107-LF-778-8099
DEPARTMENT OF THE NAVY

Memorandum

PE63:JL:jas
3960
DATE: 28 Jan 1977

FROM PE63

TO PE71 (A. F. Klarman)

SUBJ Ferrocene Test for Test Cell Smoke Abatement; evaluation of J79-GE-8D, TF41-A-2A, J57-P-10, J52-P-6B and TF30-P-6C Engine Performance and Hot Section Inspections

Ref: (a) PE71 memo PE71:AFK:sds 10340 of 11 Sep 1976

Encl: (1) J52-P-6B Engine Performance Data (Not included in Appendix)
(2) J57-P-10 Engine Performance Data (Not included in Appendix)
(3) J79-GE-8D Engine Performance Data (Not included in Appendix)
(4) TF41-A-2A Engine Performance Data (Not included in Appendix)
(5) TF30-P-6C Engine Performance Data (Not included in Appendix)
(6) Engine Parameter Changes with Ferrocene

1. This memorandum covers the results of five engines that were subjected to the reference (a) ferrocene fuel additive tests for smoke abatement. The J79-GE-8D engine hot section was examined following the ferrocene test conducted at NARF North Island during the week of 8 November 1976. The TF41-A-2A, J57-P-10, J52-P-6B and TF30-P-6C engine hot sections were examined following the ferrocene tests conducted at NARF Alameda during the weeks of 6 December and 13 December 1976. The engine calibration data with ferrocene were provided to the writer upon arrival at the NARFs. The ferrocene fuel additive was used to bring the test cell exhaust stack plume within limits defined by local pollution authorities in California. The quantity of smoke suppressant fuel additive solution injected into the engine fuel system was automatically controlled by an electronic metering system which controlled the test cell plume opacity. The fuel additive solution consisted of ferrocene and toluene which were mixed prior to the commencement of the engine tests.

2. NARF North Island Test on J79-GE-8D

A newly overhauled model J79-GE-8D engine (S/N 401801) was trimmed and calibrated with JP-5 following overhaul and also just prior to the ferrocene test. The engine was then subjected to approximately 8 hours of ferrocene, which was followed by disassembly and inspection of the hot section. It was subsequently rebuilt and calibrated using standard JP-5 fuel to ascertain it would meet the maintenance manual performance ratings at military power (intermediate power) and at maximum (afterburning) power. Plans were made to install the engine in a high-usage F-4 aircraft to accumulate time quickly, and to inspect the engine hot section during a maintenance inspection of the aircraft.

Engine test data was corrected by the writer using the method outlined in the J79-GE-8D maintenance manual except for fuel flow. There were no provisions at the NARF to correct the specific gravity changes for fuel temperature for each data point. An adjustment for specific gravity correction was made daily to the fuel flow recording instrument. The ferrocene solution injected into the engine fuel system was measured with a rotameter, and the fuel flow data of enclosure (1) was adjusted to include the ferrocene flow rate.

Originally, it was planned to operate the engine for 10 hours with JP-5 fuel following the engine rebuild, and disassemble it again for another hot-section inspection to observe carbon deposits. A J79 that was previously tested with ferrocene accumulated unusually large carbon deposits in the combustors when it was operated 1.5 hours with JP-5 following the ferrocene test. However, time ran out and only a short engine calibration was conducted the final day of the trip. Plans were made to subject this engine to 10 hours of JP-5 operation at a later date, and to observe the engine for performance degradation which might indicate carbon buildup in the combustors interfering with normal engine operation. No engine disassembly was planned at the NARF unless the engine performance degraded.

3. NARF Alameda Tests

The four engines tested with ferrocene solution at NARF Alameda were all newly overhauled, and were trimmed and calibrated following overhaul with JP-5 fuel. These engines were the TF41-A-2A (S/N 141479), J57-P-10 (S/N 627207), J52-P-6B (S/N 649859) and the TF30-P-6C (S/N 658342). The engines were operated with ferrocene solution for 8 to 10 hours during the weeks of 29 November and 6 December 1976, and they were disassembled for hot section inspections during the weeks of 6 December and 13 December 1976. It was originally planned for the NARF to rebuild the engines following the hot-section inspections, and run 10-hour JP-5 calibrations during the week of 13 December to observe any changes in engine performance. However, these plans were changed since it was necessary for the NARF to utilize their manpower to meet the production quota for the last quarter of 1976. The rebuild and test of the engines with JP-5 was postponed until after 10 January 1977. At the completion of all the testing at the NARF, it was planned to install these four engines in high-usage aircraft to accumulate time quickly, and to inspect the engine hot sections during normal maintenance of the aircraft.

Mr. E. Wold of NARF Alameda developed data programs for a Hewlett Packard portable computer to correct engine data in accordance with the respective engine maintenance manuals. Engine calibrations were usually conducted at engine ratings between 75 percent normal rated through military (or intermediate) power. The data for the four engines

was accepted as being correct. Individual engine test data and performance curves for the four engines were included in enclosures (2), (3), (4) and (5). The TF41 fuel flow was measured with one flowmeter and some of the J57 fuel flow was also measured with one flowmeter. A rotameter was utilized to measure the ferrocene solution flow rate. A correction to some of the TF41 and J57 data was made by the writer to include the ferrocene solution flow with the engine JP-5 fuel flow. However, a second flowmeter was installed to measure the combined ferrocene and JP-5 fuel flow for the J52 and TF30, and some of the J57 test data.

4. Engine Performance

Engine data trends were extracted from the performance curves of enclosures (1) through (5), inclusive, tabulated, and included as enclosure (6). Most of the data extracted was at military (or intermediate) engine power, which represented performance changes and trends that in many cases occurred at lower engine power as well as military power. Data scatter was defined as the difference between the maximum and minimum data points of the ferrocene engine calibrations at military power. Data shift was defined as the difference between preliminary JP-5 data and the average ferrocene data and whether the change was an increase or a decrease. All the engines met their specification requirements at military power with ferrocene, although in a few cases the data was marginal.

The J52, TF41 and J79 engines received JP-5 calibrations at the beginning of the ferrocene test program in addition to the engine calibration following rework. The J57 was only trimmed and checked with JP-5 following rework, which was two weeks prior to the ferrocene test. The TF30 was checked just prior to the ferrocene test, and some TF30 data following engine rebuild was received by telephone on 19 January 1977 from NARF Alameda.

J52-P-6B - The two sets of J52 preliminary data with JP-5 fuel varied nearly as much as the ferrocene test data scatter, as shown on Table 1, and any trends of the ferrocene data were not obvious.

J79-GE-8D - The J79 engine data with JP-5 following rework consisted of only one point at military and one point at afterburning to check the engine against specification requirements. It was noted on Table 1 that the J79 preliminary JP-5 data varied as much as the ferrocene data was scattered, and there was no obvious effect of ferrocene on the J79 engine. Two specific fuel consumption points that were taken during the eighth hour of calibrations were high, but noting the fluctuation at military with ferrocene between two points at six hours, it appeared the high specific fuel consumption occurred due to the fuel flow measuring technique. The fuel flows of the flowmeter and the rotameter

were combined to obtain total fuel flow. The average flow rate of 196 pounds per hour was used to correct fuel flow data at military, but the ferrocene flow rate was automatically adjusted by the engine exhaust plume opacity, and was noted to vary by 50 pounds per hour at military on the other engines that used two flowmeters.

J57-P-10 - There was not sufficient JP-5 preliminary data to substantiate how much data scatter would be typical for this engine. Engine ferrocene data scatter nearly approximated the data shift that occurred between the JP-5 data following rebuild and the ferrocene data, as shown in Table 1. Based on the JP-5 data scatter that was evidenced by the J52 and J79 engines, it appeared that the magnitude of scatter of the ferrocene data was typical for the J57 regardless of the fuel additive.

TF30-P-6C - There was also insufficient preliminary JP-5 data to substantiate how much data scatter would be typical for this engine, and NARF ALAMEDA did not normally maintain average engine data records of the engine models that were tested with ferrocene. However, some post-test JP-5 data was obtained for the rebuilt engine in a telephone conversation with Mr. E. Wold on 19 January 1977. The ferrocene data scatter for this engine was not quantitatively different from the turbojet engines, except there was a trend for the turbofan engine rotor speeds to decrease and the turbojet engine rotor speeds to increase as shown in Table 1. Comparing the preliminary JP-5 data against the post-test JP-5 data, the differences between these data nearly equalled the ferrocene data scatter. It appeared the scatter and shift of the ferrocene data could be typical for this engine regardless of whether fuel additive was utilized.

TF41-A-2A - It is recommended that the contractor be presented with the TF41 data for evaluation of the ferrocene test results. Trimming the TF41 is a complicated procedure with JP-5 fuel, and considering the apparent engine parameter changes that occurred by the addition of ferrocene, it may be very difficult to properly trim the engine with the ferrocene and JP-5 mixture. The largest data shift of all engines tested occurred to the TF41 turbine exhaust gas temperature which increased 23°F between the preliminary JP-5 calibration compared against the average value of the final ferrocene calibration and the post-test JP-5 calibration. A ballast resistor was utilized when measuring the turbine discharge temperature during eight hours of test, which cannot be compared to standard thermocouple data. The 23°F increase correlated to a 100 pounds per hour fuel flow increase.

There were some differences between the three preliminary JP-5 calibrations which were less than the ferrocene data scatter as indicated on Table 1.

An engine vibration problem was encountered during the TF41 post rebuild calibration following the hot-section inspection, as per telephone conversation with Mr. E. Wold of 20 January 1977.

TABLE 1

ENGINE PARAMETER CHANGES WITH FERROCENE - AT MILITARY POWER

Parameter	Type Data Change	J52-P-6B	J57-P-10	J79-GE-8D	TF41-A-2A	TF30-P-6C
Specific Fuel Consumption	Scatter	0.5% (0.3% w/JP-5)	1.3%	1.7% (1.4% w/JP-5)	1.8% (0 w/JP-5)	1.7%
	Shift	Random	+1.3%	Random	+1.6%	Random
High Rotor Speed (RPM)	Scatter	40 (35 w/JP-5)	20	10 (10 w/JP-5)	20 (20 w/JP-5)	60
	Shift	+40	+20	+10	-65	-100
Low Rotor Speed (RPM)	Scatter	Not Measured	22	Not Applicable	55 (93 w/JP-5)	50
	Shift		+22		0	0
Turbine Exhaust Gas Temperature (°F)	Scatter	17 (14 w/JP-5)	11	0	4	14
	Shift	Random	+11	0	+23	+14
Fuel Flow (PPH)	Scatter	0	100	232 (300 w/JP-5)	0 (100 w/JP-5)	75
	Shift	0	+110	Random	+100	+75
Turbine Exh. Gas Pressure (inHg)	Scatter	0	0.09	Not Applicable	0.24	0.15
	Shift	0	-0.09		Random	Random
Miscellaneous Parameters	Scatter	-	-	Thrust 1.5% (1.9% w/JP-5)		Low Comp.Press.Ratio 5%
	Shift			Random		+5%

5. Engine Hot-Section Inspections. All the engines received a hot-section inspection following the ferrocene test. There was no visible damage noted during the hot-section inspections of the five engines, and the iron oxide and carbon coating of the hot-section components did not appear likely to interfere with normal operation of the engines. It was possible that the dust coatings decreased the areas of the turbine nozzle guide vane stages of all the engines, but this deterioration was only evident from engine data trends of the TF30 and TF41 which both showed decreases of high rotor speed; and the TF30 showed a decrease of the high compressor pressure ratio and an increase of the low compressor ratio.

Operating the engines with the ferrocene additive resulted in soft red deposits on nearly all hot-section components in varying thicknesses. An analysis should be conducted to determine the composition of the red deposits, which were most likely a mixture of iron oxide and carbon, but were termed as iron oxide deposits for the purpose of simplifying this memorandum.

In most instances, the iron oxide deposits wiped off easily from smooth and polished surfaces. Unpolished and rough surfaces exhibited their porosity to the fine particles of iron oxide by retaining a red tint following an attempt to wipe the iron oxide dust. There were a few instances where it appeared a thin, hard coating of iron oxide formed, but only to flake off harmlessly, as with the TF41 first-stage turbine nozzle vane leading edge.

The TF30 engine, which was operated for 28 minutes with JP-5 and an additional 20 minutes with ferrocene following the ferrocene test, appeared to accumulate some soft carbon deposits on top of previous iron oxide deposits. It was uncertain whether the carbon deposits were caused by the JP-5 engine operation. The J52 accumulated carbon deposits inside the combustors which were greater than the previously inspected J79, TF41 or J57 engines; however, the J52 was operated only five minutes with JP-5 following the ferrocene test.

It cannot be speculated if any fleet problems will evolve with the engines that used the ferrocene fuel additive for engine calibrations.

a. J79-GE-8D Hot Section

The numbers three and nine combustors accumulated the most carbon and iron oxide deposits, and they along with their mating fuel nozzles were photographed in a studio. They were reinstalled in the engine. The second worst-in-appearance fuel nozzle regarding carbon buildup (number 10), the number two combustor, and two first-stage turbine blades were removed from the engine for a metallurgical examination. When the engine was rebuilt, they were replaced with new parts.

Fuel Nozzles - Some carbon buildup mixed with iron oxide deposits were noted on the face of all fuel nozzle air shrouds. A NARF representative considered the carbon deposits on two nozzle shrouds to be excessive for a total of 15.5 hours of operation. However, a flow check revealed no pattern irregularities of the number 10 fuel nozzle which had the second worst carbon buildup. The primary and secondary orifices of the fuel nozzles appeared clean and shining.

Combustors - All the combustor inner liner assemblies had a light coating of carbon in the dome area with a buildup of carbon noted on a few of the strap louvers. The rear inner liner was lightly coated with iron oxide on all the combustors. The number four combustor which contained the ignitor plug appeared no different than the other combustors. Some burns were noted on the crossover tubes, but none of these were objectionable.

Transition Duct - The transition duct, which is physically located aft of the combustors, accumulated the most iron oxide and carbon. However, the evenly distributed coating of iron oxide was loose and could be easily wiped with the finger.

Turbine Section - The first-stage turbine nozzle vanes were lightly coated with iron oxide and carbon. The remaining two stages of turbine nozzle vanes and all three stages of turbine blades were lightly coated with iron oxide dust. The turbine frame was likewise lightly coated with iron oxide dust. All the iron oxide and carbon dust coatings were loose and could be wiped with the finger.

Main Spark Plug - The main spark plug had a light coat of carbon which did not appear objectionable.

Outer Combustion Casing - Some burn marks were noted on the inside and outside surfaces of the outer combustion casing. Such a burn mark was noted at the number 10 combustor location. The number 10 fuel nozzle was flow checked, but its spray pattern was good. It appeared the burn marks on the outer casing were a cooling air distribution problem of the combustors. Iron oxide dust deposits that were noted on the exterior of some of the combustors appeared to agree in location with the burn marks of the outer combustion casing.

b. TF41-A-2A Hot Section

All the iron oxide and carbon dusting was removable with the finger except for the thin, hard red deposits on the first-stage turbine vane leading edge which were flaking. One first-stage turbine vane section had a small hole of approximately 1/64-inch diameter, which was apparently a manufacturing defect. This vane was set aside for a metallurgical examination.

Fuel Nozzle - All fuel nozzles had carbon buildup on the nozzle outer shroud which was not hard and flaked off. Four of the 10 fuel nozzles

(numbers 3, 6, 7, and 8) had some carbon deposits on the primary nozzle. There were no facilities at the engine inspection site to flow check the fuel nozzles for spray pattern without sending the nozzles out to the overhaul shop or the contractor.

Combustors - There was some light iron oxide and carbon dusting of the combustors. The numbers 7 and 10 combustors had light carbon deposits in the dome area. The numbers 4 and 8 combustors which contain the ignitor plugs were not unusual. All the combustors were noted as having some hot corrosion of tubes in the dome area.

Turbine Nozzle Vanes - The foil side of the first-stage vanes had a medium dusting, while the pressure side of the vanes had very little dusting. There was a thin, hard deposit on the leading edge of all the vanes, and some flaking of the red deposit occurred to eight vanes. The second and third-stage turbine vanes each accumulated a light red dusting of the pressure side, and a medium dusting of the foil side.

Turbine Blades - There was light iron oxide and carbon dusting of all three stages of turbine blades.

Turbine Exhaust Probes - The nine pressure and nine temperature probes were coated with iron oxide and carbon dust of medium thickness and no blockage was noted.

Turbine Exhaust Duct - Light dusting of the tailcone, vanes and duct.

Photographs - Close-up photographs were taken of the first-stage turbine vanes, and the numbers 7 and 8 fuel nozzles. All of the other photographs were overall views of components.

c. J57-P-10 Hot Section

All of the iron oxide and carbon accumulations were a dust coating which could be easily removed with the finger. The red tint which remained on some surfaces was apparently small dust particles of iron oxide lodged in between surface irregularities.

Fuel Nozzles - The J57 fuel nozzle assemblies consisted of four-cluster nozzles, but the first four assemblies had flat face type nuts and the last four assemblies had more complex nozzle nuts. The flat face-type nozzle nuts accumulated a little more iron oxide and carbon on the outer shroud than the more complex nozzle nuts. Also, there was some very light carbon buildup on the nozzle nuts of the numbers 2 and 3 assemblies. The remaining primaries were clean, and all the secondaries were clean.

Combustors - All the combustors accumulated an even red coating of iron oxide dust which was loose. There was some very light carbon buildup at the fuel nozzle cluster areas. The numbers 4 and 5 combustors which

contain the ignitors were not unusual. All combustors had burned areas of indented portions of the domes. The inner cooling air ducts, which had hot-corroded areas, were all covered with a light dust coating of iron oxide. All the combustors had up to 16 cracks each and burned areas at the dome. The number 2 combustor had sustained a 4-inch long circumferential crack of the fourth louver. It was recommended this crack be repaired since it was an obvious safety hazard.

Turbine Nozzle Vanes - The first-stage turbine nozzle vanes accumulated a very light dusting of iron oxide and carbon on the pressure side, and an average iron oxide and carbon dusting on the foil side. The second and third stages were evenly coated with iron-oxide dust.

Turbine Blades - All three stages of turbine blades accumulated a little more iron-oxide dust on the foil side compared to the pressure side.

Turbine Exhaust Duct - The exhaust duct and vanes accumulated a heavier iron-oxide dust coating. The dust coating rubbed off, but more of the red tint remained than the other engines, which was apparently due to the surface porosity. The tailcone accumulated a light dusting of iron oxide.

Turbine Exhaust Probes - The four pressure probes accumulated carbon dust two inches from the tip and iron-oxide dust on the remaining four inches. All four, 2-inch long temperature probes accumulated iron-oxide dust.

Combustion Chamber Rear - Light iron-oxide dust coating.

Photographs - Close-up photographs were taken at the numbers 2, 4 and 6 fuel nozzle assemblies. All the other photographs were overall views of components.

d. J52-P-6B Hot Section

All the iron-oxide dust deposits could be easily wiped, but on many of the components, a red tint remained which was an indication of surface porosity.

Fuel Nozzles - All fuel nozzles formed a carbon and iron oxide buildup on the outer shroud, which was soft and could easily be scraped off the shroud with a putty knife. This type of soft carbon buildup on the shroud was typical for the engine, and often the carbon accumulation was greater.

Combustors - These combustors had less iron-oxide buildup than the previously examined J79, TF41 and J57, but more carbon buildup instead. All nine domes were blackened with carbon dust and practically no iron oxide. Most iron-oxide deposits occurred on the crossover tube flanges,

which had a burnt appearance on most combustors. A very thin dust layer of iron oxide was deposited on the rear louver sections of the combustors. Nearly all crossover tubes accumulated iron-oxide and carbon deposits.

Turbine Nozzle Vanes - The first-stage turbine vanes accumulated a medium dust coating of iron oxide on the trailing portion of the foil side, and the leading edge portion of the pressure side. The second-stage vanes also accumulated a medium dust coating of iron oxide over the entire surface. The iron-oxide deposits easily rubbed off with the finger. Carbon spots were noted on the leading edge of the first-stage vanes in the area of the number 2 combustor.

Turbine Blades - There was a medium dust coating of iron oxide on the foil side of the first-stage blades, and a thin coat of iron oxide on the pressure side of the blades. The second-stage turbine blades accumulated a thin dust coating of iron oxide on both sides.

Turbine Exhaust Duct - A medium dust coating of iron oxide accumulated on the exhaust duct, tailcone and vanes.

Turbine Exhaust Probes - The three temperature and three pressure probes were coated with iron oxide and carbon dust deposits.

Photographs - Close-ups were taken of the numbers 3 and 4 fuel nozzles, first-stage vanes, first-stage blades, and the numbers 3 and 8 combustors. All the other photographs were overall views of the components.

e. TF30-P-6C

After the completion of the ferrocene test, this engine was operated for 28 minutes with JP-5 and an additional 20 minutes with ferrocene, which may have resulted in the carbon deposits on the combustors, the foil side of the first-stage turbine nozzle guide vanes, and the rear of the foil side of the first-stage turbine blades.

Fuel Nozzles - All the fuel nozzles built up soft carbon on the outer shroud. The engine was positioned vertically for inspection with the exhaust section facing up, which resulted in some of the soft carbon flaking off the outer shroud. No iron oxide was noted on the shroud of nozzle nuts from which the carbon buildup had fallen off. All the primary and secondary orifices were clean.

Combustors - All the combustor dome areas were blackened with carbon, but this carbon duct coating when wiped left a red sub-coating or tint. There was also a carbon coating of the crossover and ignitor tubes, which rubbed off to expose a sub-layer of iron oxide. All the combustors accumulated very light iron-oxide deposits on the exterior at a hole next to the crossover tube, which could be easily wiped. Apparently, the use of ferrocene revealed a slight cooling air distribution problem of these combustors.

PE63:JL:jas

Turbine Nozzle Vanes - The first-stage turbine nozzle vanes accumulated an unusual heavy carbon dust and iron-oxide coating over the entire foil side, but the pressure side was typical. The carbon and iron oxide easily wiped off. The second-stage vanes accumulated a carbon and iron-oxide dust coating which easily wiped off, but the pressure side accumulated a thin, harder coating of iron oxide. The third and fourth-stage vanes had an average iron-oxide coating which wiped off easily but left a red tint.

Turbine Blades - The first-stage turbine blades had a medium iron-oxide coating mixed with carbon on the trailing half of the foil side, and a thin iron-oxide coating on the leading half of the foil side. The high pressure side of the first-stage turbine blades had a light coat of iron oxide with some carbon dust. The second-stage turbine blades had a medium iron-oxide coat on the trailing portion of the foil side; a light iron-oxide coat on the leading portion of the foil side; and a thinner coat of iron oxide on the pressure side. There was a thin coat of iron oxide deposited on the surfaces of the third and fourth-stage blades.

Engine Exhaust Duct - The outer duct was coated with a medium layer of carbon dust. The tailcone, three large exit vanes and numerous small vanes were coated with iron oxide. The inner duct forward of the tailcone was mostly coated with carbon dust and some iron oxide.

Turbine Exhaust Probes - The six temperature and pressure combination probes were mostly covered with iron oxide which was mixed with some carbon.

Turbine Outer Air Seals - The numbers 2, 3, and 4 turbine outer air seals, which were normally rough due to the plazma coating process, absorbed iron oxide dust particles which could not be wiped off. The first-stage turbine outer air seal appearance was not unusual.

Photographs - Close-ups were taken of the number 7 combustor crossover tube (where a portion of carbon was wiped off to expose the iron oxide sublayer); and the first-stage turbine blade leading edge and trailing edge. Overall views were taken of the engine hot section components.

John Lezniak

JOHN LEZNIAK

ENGINE PARAMETER CHANGES WITH FERROCENE

	J52-P-6B	J57-P-10	J79-GE-8
Specific Fuel Consumption	0.5% data scatter at military. There was 0.3% difference between the two initial JP-5 calibrations. SFC data below the specification limit at military.	1.3% data scatter at military. Average ferrocene data shifted 1.3% above initial JP-5 calibration. SFC data below the specification limit at military. There was a 2.2% spread of all the test data at military.	1.4% difference of JP-5 data. 1.7% scatter of majority of data at military. Some military data at 6 and 8 hours were higher, which would increase data scatter to 3.5%, but it appeared this was caused by the fuel flow and ferrocene measuring technique. Engine met SFC requirements at military and afterburning.
High Rotor Speed	40 rpm (0.35%) data scatter at military. Speed increased 40 rpm at military during hours 4 thru 10 with ferrocene. There was 35 rpm difference between the two initial JP-5 calibrations.	20 rpm (0.2%) data scatter at military. Speed increased 20 rpm at military during hours 9 thru 11 with ferrocene.	A speed increase of 10 rpm was noted during the eighth hour of ferrocene, which was also the scatter. Engine rotor speed varied from 7683 to 7706 rpm (0.3%) at military and afterburning during all JP-5 fuel and ferrocene solution calibrations. This was within the engine speed versus compressor inlet temperature limits of 7647 to 7723 rpm.
Low Rotor Speed	Not measured.	22 rpm (0.4%) data scatter at military. Speed increased 22 rpm at military during hours 9 thru 11 at military.	Not applicable.
Turbine Exhaust Gas Temperature	17°F (1.6%) random data scatter at military. There was 14°F between the two initial JP-5 calibrations.	EGT increased 11°F (1.1%) from initial JP-5 calibration to average of ferrocene data at military. Ferrocene data showed 11°F of scatter.	EGT measured 1160°F at all military and afterburner data points. EGT was initially set according to the exhaust gas temperature versus engine speed limits of 1152° to 1175°F.
Fuel Flow	Very little data scatter.	Fuel flow increased 110 pph (1.4%) from initial JP-5 calibration to average of ferrocene data at military. Ferrocene data showed 100 pph scatter.	There was data scatter of 232 pph (2.5%) at military. The data scatter of the initial JP-5 calibrations of nearly 300 pounds included all the subsequent ferrocene and final JP-5 data.

	J52-P-6B	J57-P-10	J79-GE-8
Engine Pressure Ratio versus Thrust (J79-Thrust)	EPR data spread between the second initial JP-5 calibration and ferrocene test data was neglibable. However there was a difference of 0.005 ratios ($\triangle P_{T7}$ = 0.15 in Hg) between the two preliminary JP-5 calibrations at military.	EPR data shifted downward 0.003 ratios ($\triangle P_{T7}$ = 0.09 in Hg) at military and 0.006 ratios at maximum continuous during 9 thru 11 hours of ferrocene testing.	Thrust - Data scatter of 165 pounds (1.5%) occurred at military power. The final JP-5 calibration was 174 pounds (1.6%) higher than the initial JP-5 calibration. The initial JP-5 calibrations showed a difference of 208 pounds (1.9%). Engine military and afterburning (not shown) thrust was greater than the minimum allowable thrust during the test program.
	TF41-A-2A	TF30-P-6C	
Specific Fuel Consumption	1.8% scatter of ferrocene data proximity of military rated power. Average ferrocene data shifted 1.6% above initial JP-5 calibrations. Extrapolated engine data was marginal when compared to the SFC specification limit maximum value at intermediate power.	1.7% scatter of ferrocene data at military. Average ferrocene data for hours 5 thru 8 shifted 1.2% above ferrocene data for the first 4 hours.	
High Rotor Speed	Speed showed a decrease of 65 rpm (0.5%) at military when comparing the two initial JP-5 calibrations against ferrocene test data during hours 8 and 9 and the final JP-5 calibration. Military power ferrocene data scatter was less than 20 rpm during hours 8 and 9.	60 rpm (0.4%) scatter of the ferrocene data at military. Average ferrocene data shifted 100 rpm below the initial JP-5 calibration.	
Low Rotor Speed	Military power ferrocene data scatter was 55 rpm during hours 8 and 9. There was a difference of 93 rpm at military between the three sets of preliminary JP-5 data.	50 rpm (0.5%) data scatter of ferrocene data. At normal rated power during 8 hours of ferrocene speed decreased 39 rpm (0.4%).	
Turbine Exhaust Gas Temperature	EGT showed an increase of 23°F (1.9%) between 75% and intermediate when comparing one initial JP-5 calibration against ferrocene test data during hours 8 and 9 and the final JP-5 calibration. 4°F scatter of ferrocene data at military. A ballast resistor was used during the first 8 hours of the test program when measuring EGT which could not be directly compared to the standard engine EGT.	14°F (0.5%) data scatter at military. Calibrations progressively increased 14°F from the initial JP-5 calibration thru the 8 hours of ferrocene.	

	TF41-A-2A	TF30-P-6C
Fuel Flow	Fuel flow showed an increase of 100 pph (1.1%) at intermediate power when comparing the three initial JP-5 calibrations against the ferrocene test data. There was a difference of 100 pph between the three JP-5 calibrations at military. There was no scatter of ferrocene data during hours 8 and 9.	75 pph (1.1%) data scatter at military. Calibrations progressively increased 75 pph from the initial JP-5 calibration thru the 8 hours of ferrocene.
Engine Pressure Ratio versus Thrust	EPR data showed random spread of 0.008 ratios ($\triangle P_{T5.1}$ = 0.24 in Hg).	EPR data showed random spread of 0.005 ratios ($\triangle P_{T7}$ = 0.15 in Hg).
High Compressor Discharge Pressure or Pressure Ratio	The high compressor discharge pressure showed a 3 in. Hg (0.5%) decrease with ferrocene. There was very little ferrocene data scatter.	*The high compressor discharge pressure ratio* data collected during the eight hours with ferrocene was 0.39 ratios (2.6%) below previous data at normal rated and military. All the previous calibrations showed little data scatter.
Low Compressor Discharge Pressure Ratio	Not measured.	The low compressor discharge pressure ratio data collected during the eight hours with ferrocene was 0.22 ratios (5%) higher than previous data at normal rated and military. All the previous data thru 7 hours of ferrocene showed 0.08 ratios (2%) scatter. The JP-5 calibration following hot section rebuild was also 5% higher than previous data.

APPENDIX E

AIR FORCE EVALUATION OF J79-GE-8D HOT SECTION COMPONENTS

VISUAL REPORT, J79-GE8 HOT SECTION PARTS

BY: KEN HOPKINS/AFAPL/TBC/55421

TO: CHARLES R. MARTEL/AFAPL/SFF

DATE: 2 MARCH 1977

1. BACKGROUND:

Several hot section parts from a J79-GE8 were brought to the Air Force Aero-Propulsion Laboratory, Components Branch, Combustion Technical Area (AFAPL/TBC) for visual inspection and report. The engine had been run for about 10 hours in a Naval Air Propulsion Test Center (NAPTC) test cell using JP-5 containing ferrocene. The object of the test was to determine whether the introduction of ferrocene, a smoke abatement agent, during relatively short test cell operations would have any adverse affects on the life and health of the engine. This report is based on observation.

2. OBSERVATIONS:

The reviewed parts were one (1) combustor liner (Figures 1 through 5), two (2) first-stage turbine blades (Figure 6) and one (1) fuel nozzle (Figure 7).

The inside of the combustor liner was orange in color (Figures 1 through 5). This orange film was loosely attached as it could be wiped off. This can be seen in the fingerprint smears in Figure 1 at the 3 o'clock position near the liner exit. However, some of the orange film seems to be attached firmly.

The liner showed some evidence of warm streaking but only one streak stood out (Figure 2 at the 4 o'clock position near the liner exit and seen also in Figure 3 at the 1 o'clock position.

Liner cracking was non-existent.

There was some discoloration on the outside of the liner but this was not a deposit but rather caused by temperature. The warm streak mentioned above, when viewed from the outside seems to be a cool area.

In Figure 4, the warm streak appears at 10 o'clock where there is no metal discoloration. Note, however, the 8 o'clock position has obviously been operating at a higher temperature as shown by the discolored louvers.

The first-stage turbine blades were orange to red in color (Figure 6). This coating is apparently the same as that on the combustor liner. There was no evidence of cracking, oxidation or other distress.

The fuel nozzle appeared to have a limited thickness of orange coating on the radiation shield (or cooling shroud). The build-up of carbon seemed to be thicker than the orange coating (Figure 7).

3. CONCLUSIONS AND RECOMMENDATIONS

The orange coating on the liner should not shorten its life unless it metallurgically weakens the liner (to be determined by others) or it dramatically increases the liner surface emissivity. Since most coatings and oxides possess emissivities of at least 0.8 with none above 0.9, the increase in emissivity is not expected. If the emissivity increases significantly, the liner temperature increases which could shorten its life and also could lead to combustor case burn-through. Although this is not expected, it cannot be rejected. However, if the orange coating is removed by operating the engine with pure JP5, this potential problem would be solved. A ground test would be sufficient to determine this if the ambient air does not contain impurities that are commonly called "iron oxide" by ground test personnel.

The warm streak is not unusual. The J79 usually possesses warm streaks and hot streaks. However, this reviewer is not accustomed to inspecting parts that were subjected to only 10 operating hours.

The build-up on the fuel nozzle shroud appears to be thicker than on the other parts. Build-up can be serious because it distorts the fuel spray. The build-up should be investigated to determine if it is predominantly ferrocene or of hydrocarbon origin. If it is ferrocene, it could affect the life of the engine if: (1) it is unusually thick compared with normal carbon deposits after 10 hours operating time, and (2) it persists after operation with pure JP5.

Kenneth N. Hopkins

KENNETH N. HOPKINS
Aerospace Engineer
Components Branch
Turbine Engine Division

7 Atch
Figures

SYSTEMS SUPPORT DIVISION
AIR FORCE MATERIALS LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

EVALUATION REPORT

J-79-8 ENGINE HOT SECTION PARTS

REPORT NR: AFML/MX 77-15 DATE: 17 February 1977

PROJECT NR: 327Z TYPE EVALUATION: Metallurgical

MANUFACTURER: SPEC NR:

SUBMITTED BY: AFAPL/SFF (Mr. C. R. Martel) ITEM SERIAL NR:
WPAFB, OH 45422

I. PURPOSE:

To conduct a metallurgical examination of J-79-8 engine hot section parts to identify bright orange colored deposits on the components and determine the effect of the deposits on the metal microstructures.

II. FACTUAL DATA:

1. A combustor can, a fuel nozzle and two high pressure first stage turbine blades from a J-79-8 engine were submitted to AFML/MXA for metallurgical analysis.

2. The parts came from an engine which had been used in a program to suppress smoke at jet engine test stands. The engine had been subjected to 10 hours of operation using JP-5 fuel containing an anti-smoke additive, ferrocene. The introduction of ferrocene resulted in bright orange deposits on the parts examined. A photograph of the parts submitted is shown in Figure 1. The orange deposit can be readily seen on the turbine blades. The combustor can has the deposits on the inside and there is very little on the nozzle. The nozzle does exhibit some black deposits which are not readily seen in the photograph.

3. The orange deposits were analyzed and found to be iron oxide (Fe_2O_3). The black deposits on the nozzle turned out to be carbon.

4. Cross sections of metal containing iron oxide coatings were examined metallographically. The microstructures observed showed no effects which could be attributed to the presence of the oxide coating. A section of a turbine blade, Figure 2, shows a typical cast microstructure for Udimet 500 which is the base material. The nozzle is stainless steel and the combustor can is Hastelloy X. Figure 2 also shows that the blades were coated. This coating is proprietary and is applied during fabrication of the blade and is not related to the iron oxide deposits.

THIS REPORT IS NOT TO BE USED IN WHOLE OR IN PART FOR ADVERTISING OR SALES PROMOTION PURPOSES

5. In addition to microscopic examination, all the parts were X-rayed and dye penetrant inspected. These examinations showed that the components were all structurally sound. There were no defects and no evidence that the oxide deposits had in any way had an adverse effect on the base metal.

III. CONCLUSIONS:

1. The bright orange deposit on the combustor, nozzle and turbine blades is iron oxide (Fe_2O_3).

2. The oxide deposits had no effect on the metal microstructure and nondestructive examination (NDE) showed all parts were structually sound.

IV. RECOMMENDATIONS:

None, data merely submitted.

COORDINATION:

Bennie Cohen

BENNIE COHEN, AFML/MXA

PREPARED BY:

Paul L. Hendricks

PAUL L. HENDRICKS, AFML/MXA

PUBLICATION REVIEW

This report has been reviewed and is approved.

T. D. Cooper

T. D. COOPER, Chief
Materials Integrity Branch
Systems Support Division

DISTRIBUTION:

AFML/MX
AFML/MXA (3 cys)
AFML/MXE (Mr. Olevitch)
AFML/NA
AFWAL
AFML/DOC/MIC (Library)
AFAPL/SFF (Mr. C. R. Martel)

Figure 1. Photograph of the engine parts showing the bright orange deposits.

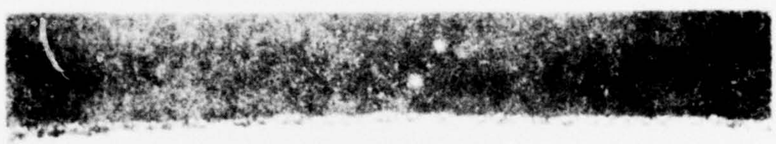


Figure 2. Photomicrograph from a blade cross section showing typical cast microstructure for Udimet 500 and proprietary coating on the surface. MAG: 100X

DISTRIBUTION LIST

	COPIES
Naval Air Systems Command (AIR-954), Department of the Navy Washington, DC 20361	10

Intra-Command Addresses

AIR-01B	(1)	AIR-50184	(1)
AIR-330D	(1)	AIR-53431B	(1)
AIR-340E	(1)	AIR-536B1	(1)
AIR-4147A	(1)	AIR-53645A	(1)

Defense Documentation Center for Scientific and Technical Information (DDC), Bldg. No. 5, Cameron Station, Alexandria, Virginia 22314	12
Chief of Naval Operations, Navy Department, Washington, DC 20361 (Codes: OP451, OP453)	2
Chief of Naval Material, Navy Department, Washington, DC 20361 (Codes: 08T241, 044P1)	2
Commander, Naval Air Force, U.S. Pacific Fleet, Naval Air Station North Island, San Diego, California 92135 (Code: 722)	1
Commander, Naval Air Force, U.S. Atlantic Fleet, Naval Air Station Norfolk, Virginia 23511	1
Commander, Naval Aviation Logistics Center, Naval Air Station, Patuxent River, Lexington Park, Maryland 20670 (Code: 2223)	1
Commanding Officer, Naval Air Rework Facility, Naval Air Station North Island, San Diego, California 92135 (Codes: 361, 642, 64270 (3))	5
Commanding Officer, Naval Air Rework Facility, Naval Air Station Alameda, California 94501 (Code: 642)	3
Commanding Officer, Naval Air Rework Facility, Naval Air Station Jacksonville, Florida 33212 (Code: 610)	1
Commanding Officer, Naval Air Rework Facility, Marine Corps Air Station, Cherry Point, Cherry Point, North Carolina 28533	1
Commanding Officer, Naval Air Rework Facility, Naval Air Station Norfolk, Virginia 23511	1
Commanding Officer, Naval Air Station, Miramar, San Diego, California 92135	1
Commanding Officer, Naval Air Station, Lemoore, California 93245	1

	COPIES
Commander, Pacific Missile Test Center, Point Mugu, California 93042	1
Commander, Naval Facilities Engineering Command, 200 Stovall Street, Alexandria, Virginia 22332 (Codes: 104, 032B)	2
Commanding Officer, Naval Facilities Engineering Command, Western Division, San Bruno, California 94066 (Codes: 09BE, 114 (3))	4
Commanding Officer, Naval Construction Battalion Center, Port Hueneme, California 93043 (Codes: 25, 251, 252)	3
Bureau of Medicine and Surgery, Navy Department, Washington, DC 20372 (Code: BUMED 5622)	1
Navy Environmental Health Center, 333 Vine Street, Cincinnati, Ohio 45220 (Code: 1)	1
Naval Medical R&D Command, National Navy Medical Center, Bethesda, Maryland 20014 (Attn: LCDR Doptis)	1
Commandant of the Marine Corps, Department of the Navy, Washington, DC 20380 (Code-AAJ)	1
Commanding General, Marine Corp Air Station, El Toro, California 92709	1
Commanding General, Marine Corp Air Station, Yuma, Arizona 85364	1
U.S. Air Force, Headquarters, Washington, DC 20330	1
Detachment 1 (Civil and Environmental Engineering Division Office), Headquarters ADTC (AFSC), Tyndall Air Force Base, Florida 32403 (Code: ECA)	6
OC-ALC/MMPRE, MAET, Tinker Air Force Base, Oklahoma 73145	2
Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433 (Code: MXA)	1
Air Force Systems Command, Andrews Air Force Base, Washington, DC 20334 (Code: DEV)	1
Arnold Engineering Development Center, Arnold Air Force Station, TN 37342 (Code: DYR)	1
Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio 45433 (Codes: SFF, TBC)	2

	COPIES
Air Force Logistics Command, Wright-Patterson Air Force Base, Texas 78235 (Code: MAXF, MAUT, DEP, LOP)	4
Army Aviation Systems Command, P.O. Box 209, St. Louis, Missouri, 62166 (Code: EQP)	1
Eustis Directorate, USA AMR & DL, Ft. Eustis, Virginia 23604 (Code: SAVDL-EU-TAP)	1
Federal Aviation Administration, National Aviation Facility Experimental Center, Atlantic City, New Jersey 08405 (Code: ANA-420)	1
Detroit Diesel, Allison Division, Indianapolis, Indiana 46206 (Attn: J. Tomlinson, J. Vaught)	2
United Technologies Corporation, Pratt and Whitney Aircraft Division, E. Hartford, Connecticut 06108 (Attn: J. Elwood, A. Nelson)	2
General Electric Co., Advanced Engine Group, Evendale, Ohio 45215 (Attn: R. Williamson, C. Strandorth)	2
United Technologies Corporation, Pratt and Whitney Government Products Division, Box 2691, West Palm Beach, Florida 33402 (Attn: S. Bonifazi)	1
Air Force School of Aerospace Medicine, Brooks Air Force Base, Texas 78235 (Code: VNL)	3